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THESIS

U.S. CHEMICAL WARFARE STOCKPILE VULNERABILITY: EFFECTS TO LOCAL INFRASTRUCTURE FROM A CHEMICAL-AGENT RELEASE

by

Jeffrey Sundberg

June 2007

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This thesis develops methods to identify certain infrastructure vulnerabilities from the accidental or intentional release of a chemical agent from a U.S. Chemical Warfare Stockpile and Facility (CF). For the region surrounding any CF, a "multi-infrastructure network operations model" (MINO) is created from various infrastructure datasets: MINO covers the local population, road network, and emergency-response systems. Standard software generates a chemical-agent-release scenario that requires the evacuation of part of the region, and that blocks emergency responders from using certain roads. Using shortest-path methods, one version of MINO then identifies evacuation routes that the local population will likely use, showing where traffic congestion may slow evacuation. Another version computes and compares emergency-response distances, pre-release and post-release, for areas outside the contaminated region. Two or three scenarios are examined for each of six CFs. The areas surrounding Newport, Indiana, and Pueblo, Colorado, CFs show low evacuation numbers and low traffic intensities. For the Anniston, Alabama; Blue Grass, Kentucky; and Umatilla, Oregon CFs, several roads exhibit high traffic intensities that may slow evacuations. Several of these scenarios, along with one Pueblo incident, also show significant travel-distance increases for emergency-responders. Software limitations prohibit analysis of the CF at Tooele, Utah.

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U.S. CHEMICAL WARFARE STOCKPILE VULNERABILITY: EFFECTS TO LOCAL INFRASTRUCTURE FROM A CHEMICAL-AGENT RELEASE

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This thesis develops methods to identify certain infrastructure vulnerabilities from the accidental or intentional release of a chemical agent from a U.S. Chemical Warfare Stockpile and Facility (CF). For the region surrounding any CF, a “multi-infrastructure network operations model” (MINO) is created from various infrastructure datasets: MINO covers the local population, road network, and emergency-response systems. Standard software generates a chemical-agent-release scenario that requires the evacuation of part of the region, and that blocks emergency responders from using certain roads. Using shortest-path methods, one version of MINO then identifies evacuation routes that the local population will likely use, showing where traffic congestion may slow evacuation. Another version computes and compares emergency-response distances, pre-release and post-release, for areas outside the contaminated region. Two or three scenarios are examined for each of six CFs. The areas surrounding Newport, Indiana, and Pueblo, Colorado, CFs show low evacuation numbers and low traffic intensities. For the Anniston, Alabama; Blue Grass, Kentucky; and Umatilla, Oregon CFs, several roads exhibit high traffic intensities that may slow evacuations. Several of these scenarios, along with one Pueblo incident, also show significant travel-distance increases for emergency-responders. Software limitations prohibit analysis of the CF at Tooele, Utah.

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EXECUTIVE SUMMARY

This thesis examines the effects to the functionality of local infrastructure in the event of a major chemical-agent release from one of the remaining United States Chemical Warfare Stockpiles and Facilities (CFs). A multi-infrastructure network operations model (MINO) represents the interactions between the local population and certain infrastructure, specifically, the road network and the emergency-response system (ERS). For any catastrophe scenario, MINO highlights road segments that may become overburdened by evacuees, and identifies areas with degraded access by emergency responders and to hospitals.

Several steps are necessary to build and solve each instance of MINO. For each CF, the first step builds an interconnected MINO network model that links the local population and emergency-response systems through the local road network. U.S. Census 2000 data provides population data by "block" (small census tract), and provides road data. Emergency-response system data, which includes hospital facilities, fire stations, Emergency Medical Services, and ambulance providers, is derived from a database provided by the National Geospatial-Intelligence Agency (NGA).

A commercial dispersion model HPAC (Hazard Prediction and Assessment Capability) defines a "chemical-agent-release scenario" based on several parameters, including type of chemical agent, release point, wind speed and wind direction. The scenario describes the area that is likely to be contaminated. (Two or three scenarios are analyzed for each CF.) MINO then expands the contaminated region with a buffer zone, to create an "evacuation area," and assumes that (1) all people within the evacuation area must evacuate, and (2) after evacuation, no emergency services may use any roads within the evacuation area, nor may anybody seeking to reach a hospital use one of those roads. Finally, MINO applies two models, an evacuation model and an emergency-response-system (ERS) model, to analyze the effect that the estimated road restrictions have on evacuation and emergency response.

The evacuation model assumes that each population group (population in a census block) within the evacuation area will follow their shortest route to leave that area. The

model computes these routes with a standard shortest-path algorithm. (By computing evacuation routes backwards, only a single shortest-path calculation is needed.) With evacuation paths for each population group defined, traffic intensity on each road segment in the evacuation area is computed, and heavily used roadways are highlighted. The results also identify areas outside the evacuation area that will encounter the most evacuees. This may be important for emergency planning of food, shelter, medical care, etc.

The ERS model investigates how, after the catastrophe, unusable pieces of the road network affect the response distances for emergency responders working in the evacuation area, and distances required by the population to reach hospital facilities. The model calculates ERS distances and "closest-hospital distances" for all population groups, pre-release and post-release, within the evacuation area. The difference between these two results is mapped graphically to highlight areas that may experience severely degraded emergency services, or none at all.

Wind direction significantly affects results in the two or three scenarios analyzed for each CF. Results for the Newport Chemical Depot, Indiana, show a robust road and ERS network that provides multiple exit routes for evacuating traffic and redundant coverage for emergence-response systems. Scenarios for the Anniston Chemical Activity, Alabama, show larger impacts because of a larger local population. Except for a few areas, changes in ERS distances are small in the Anniston scenarios, however.

The area surrounding the Blue Grass Chemical Activity, Kentucky is heavily populated, but two scenarios, using seasonally prevailing winds, show no mass evacuations because neither resulting evacuation area covers a major city. However, with several road segments exhibiting high-intensity traffic, the evacuations are still significant events. ERS distances also increase in many areas to the west of Blue Grass. For the Pueblo Chemical Depot, Colorado, prevailing winds imply almost no impact to the population and infrastructure modeled by the MINO. However, a worst-case scenario, with wind blowing into the city of Pueblo, creates a mass evacuation, closes all hospitals in the model area, and significantly increases emergency-response distances southeast of the city.

Major differences appear in evacuation results for the two scenarios examined for the Umatilla Chemical Depot, Oregon. Nearly 100,000 more people evacuate in one scenario than the other. In the worst case, ERS capabilities are also heavily affected, because a large number of evacuees become isolated from hospital facilities.

Because of the network's design and implementation, software limitations did not allow analysis of the region surrounding the Deseret Chemical Depot, Utah.

MINO should be useful for assessing and guiding improvements in existing emergency-response plans near CFs. Its methods could also be applied to chemical, biological, and nuclear disasters, and to certain natural disasters like floods.

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I. INTRODUCTION

A. OVERVIEW

This thesis investigates and models the effects of a malicious or accidental release of a chemical agent upon infrastructure located at and near Chemical Warfare Stockpiles and Facilities (CFs) in the United States. Research addresses cascading effects to select infrastructure, specifically road networks, public-health systems, and emergency-response systems. The ultimate purpose is to identify road segments that are critical for effective evacuation of a contaminated or soon-to-be contaminated area, and how emergency-response times may increase in the "safe area," just outside the area to be evacuated.

B. BACKGROUND AND MOTIVATION

This thesis is developed in cooperation with USNORTHCOM-NORAD/J2, Joint Intelligence Operations Center North, in support of the defense of the Homeland. The motivation comes from a need to identify infrastructure that is vulnerable to the accidental or malicious release of a chemical-warfare agent from a CF, where these agents are being stored and destroyed.

The U.S. no longer produces chemical agents, and has agreed to completely destroy all chemical-weapons, chemical-agent inventories, and production facilities (CMA 2007a). Two CFs have completed or nearly completed destruction of their agents, and the other six have relatively firm "destruction schedules" in place. But, until all agents are destroyed by 2023 (Eisler 2006), emergency-preparedness planners and military agencies must continue to improve contingency plans for a catastrophic chemical-agent release. This thesis will help identify and characterize certain related infrastructure vulnerabilities to assist contingency planners.

In the event of a chemical-agent release, efficient evacuation of the contaminated area will be a top priority for public safety. One model developed in this thesis, the

"evacuation model," identifies road segments that may become over-capacitated during an evacuation: this can alert officials to take appropriate traffic-control measures and plan alternate routes around congested areas. Using an "emergency-response system model," this thesis also examines the effect of a chemical-agent release on emergency-response systems by identifying areas that may suffer from degraded emergency-responder services, and by identifying areas that may be isolated from hospitals or other emergency care. Here "planners," hereafter defined as emergency preparedness planners, military contingency planners, local agency planners, etc., could consider alternate transportation options or identify non-local emergency-response services to augment local ones.

C. METHODOLOGY

The thesis first characterizes the operational environment surrounding each CF of interest, including the composition of its stockpile and the planned destruction schedule. A summary of chemical-agent effects upon specific infrastructure systems includes a description of the likely impact to those infrastructures. With a chemical-agent release into the environment from a known CF—such a release is hereafter referred to as a "chemical catastrophe"—analysis will examine the effects on a few of several possible infrastructure systems.

Utilizing modeling and simulation to analyze the effects of chemical catastrophe is not new. In fact, an existing dispersion model will be used in this thesis to estimate the extent of the contamination area. Certain research in evacuation modeling for large geographical areas suggests simulation as a method to analyze traffic flow (Li et al. 2006, Han et al. 2006). Other literature suggests the use of optimization, networks, and dynamic flows for analytical purposes (e.g., Mamda et al. 2004, Liu et al. 2005).

In Mamda, et al., they suggest shortest-path and quickest-path approaches using multiple sinks, and they also describe a dynamic network model with a time element to address traffic congestion. Although the time factor is beyond our scope, the discussion of static networks using multiple sinks is useful. In the study of hurricane evacuation by Liu, et al., optimization is used to identify traffic control plans, but then simulation is used for the evacuation. However, Liu, et al., does discuss the critical issue of emergency

response team routing, but leaves it for further study. This thesis chooses a network-optimization approach that uses shortest-path techniques to identify routes for evacuees, emergency responders, and people trying to reach hospital facilities.

For each CF, a multi-infrastructure network-operations model, $MINO_{NET}$, is constructed with several sets of infrastructure data, e.g., road data, population census data, hospital locations. A chemical catastrophe at a CF is then posited, defined by parameters for agent type, wind speed and direction. Standard chemical-agent-dispersal software calculates agent dispersal based on those parameters, and a contaminated area is calculated. An "evacuation area" is then defined, consisting of the contaminated area plus a buffer zone around that area; all people must evacuate from the evacuation area, and all vehicle traffic is forbidden in the area after evacuation. Two application models are then built on top of $MINO_{NET}$ to examine two "interdependent-infrastructure contingency events"; population evacuation from the designated evacuation area, and the effect on emergency-response systems (ERSs) after the evacuation. We refer to these two "contingency-response models" as $MINO_{EVAC}$ and $MINO_{ERS}$, respectively. We use "MINO" as a generic term to mean the application of $MINO_{EVAC}$ and/or $MINO_{ERS}$ to $MINO_{NET}$, along with ancillary computations to put data into the correct format for input, output, and analysis purposes.

$MINO_{EVAC}$ uses shortest-path methods to estimate traffic intensity on the road network resulting from the local population evacuating the evacuation area. Estimated traffic intensity on each road segment points to segments that are critical for effective evacuations. By identifying over-capacitated roadways, planners can adjust disaster plans by considering alternate routes for evacuation and emergency services, allocation of police for traffic control, and other measures. With the mapping of expected traffic routes and population flow, $MINO_{EVAC}$ can also identify nearby regions that will need to absorb large numbers of potentially contaminated evacuees. This information can be used to make special planning arrangements for food, shelter, medical care, etc.

$MINO_{ERS}$ uses a similar methodology to calculate the "shortest-response distance" from each "population group" to the nearest hospital and the nearest emergency responder. (Population groups, also used in evacuation modeling, aggregate the

population in a census tract into a single homogeneous group.) After the chemical catastrophe, emergency responders and the local population are prohibited from using the road network in the evacuation area for travel. $MINO_{ERS}$ compares the response distances for hospitals and emergency responders after the chemical catastrophe (with travel prohibitions imposed) to the normal distances. This distribution of increased ERS distances for each population group, when mapped geographically, highlights areas with no nearby hospital facilities and emergency responders. Planners should consider augmenting emergency services or dedicating transportation services to supplement the remaining ERS capabilities, for any area with a significantly increased ERS distance. Ultimately, planners can use these results to improve emergency courses of action and emergency preparedness plans.

D. SCOPE, LIMITATIONS, AND ASSUMPTIONS

This thesis is not meant to be an authoritative source for understanding the basic characteristics and effects of chemical agents. The cause of the chemical catastrophe is not the focus of this thesis; the catastrophe is an assumed event. Given that the event occurs under posited environmental conditions—these conditions define a "scenario"—an existing model (DTRA 2004) identifies the dispersion plume for the catastrophic chemical-agent release and determines "the contaminated area." Only a few catastrophe-scenarios are modeled for each CF analyzed, and actual incidents could vary significantly from these scenarios.

The geographical area covered by each scenario is limited to keep the resulting network model from exceeding the capabilities of analytical software, specifically Microsoft Excel (Walkenbach 2004). The spreadsheet limitations of Excel, specifically, the maximum number of rows and columns, are the primary factors constraining the size of network analyzed. In fact, because of these limitations, of the six CFs for which analysis would be useful, only five are analyzed in this thesis. The road network surrounding one CF is simply too complex for the current software implementation to handle.

E. THESIS ORGANIZATION

Chapter II begins with a short primer on chemical agents stored at CFs in the United States. The chapter continues with an operational environment assessment for each CF, and then discusses general effects chemical agents could have on exposed infrastructure systems. Chapter II ends with a description of the software used for calculating the contaminated areas for the various chemical-catastrophe scenarios.

Chapter III describes the methods used for analyzing effects on local infrastructure. First, the multi-infrastructure network-operations model ($MINO_{NET}$) is developed. Next, the thesis describes the construction of hypothetical chemical-catastrophe scenarios. The rest of Chapter III develops MINO further, and describes the two contingency-response models, $MINO_{EVAC}$ and $MINO_{ERS}$ built on top of $MINO_{NET}$. Chapter IV applies the $MINO_{EVAC}$ and $MINO_{ERS}$ to each CF, for two or three scenarios, and describes results. Chapter V summarizes the thesis, points out key insights gained and recommends areas for future work.

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II. OPERATIONAL-ENVIRONMENT ASSESSMENT

This chapter briefly describes the chemical agents previously produced and now stored by the United States, for different types of weapons. (More detail can be found in Army Field Manual 3-9, Potential Military Chemical/Biological Agents and Compounds; see Department of the Army 1990.). Subsequently, a detailed operational-environment assessment for each CF describes its chemical-agent inventory and destruction plans. Finally, the chapter describes the likely effects of chemical agents on the infrastructure systems of interest in this thesis.

A. U.S. CHEMICAL AGENTS

The majority of U.S. chemical-weapon agents are of two basic types, nerve agents and blister agents. These agents may exist as solids, liquids, or gases, depending on how they were produced and how they are stored. Chemical agents are designed to kill, seriously injure, or incapacitate people. The effects on infrastructure systems such as roads and buildings are not well known, but chemical agents can persist and remain lethal within those systems for up to 16 weeks (DTRA 2001).

1. Agent Persistence

Determining the length of time that an agent retains lethality, i.e., its "persistence," is important for any operations or activity in and around a contaminated area. Several factors influence the persistence of chemical agents, including the type of agent, the agent's volatility, and local weather, and terrain. In general, nerve agents and blister agents are the least volatile and the most persistent of chemical agents. The United States maintains no inventories of other agents, such as blood and choking agents.

Weather can affect an agent in several ways. Wind can disperse an agent rapidly in open country so that its concentration becomes non-lethal; however, the contaminated may also increase in size with wind dispersion, and an agent may be blown into terrain and vegetation that can increase its persistence. High temperatures decrease, and low

temperatures increase, persistence (DTRA 2001). Rain disposes, dilutes and promotes hydrolysis of an agent and thus reduces an agent's lethality. However, rain does not neutralize any agents (DTRA 2001).

The terrain and vegetation in an affected area also play a key role in determining persistence. Chemical agents tend to flow over rolling terrain and follow the contours of the earth's surface, with the heavier concentrations remaining close to the ground. Areas of heavy vegetation reduce wind speed and sunlight, thereby increasing persistence (DTRA 2001).

Importantly, the nerve agents and blister agents stored in U.S. CFs are highly persistent. Following a chemical catastrophe with one of these agents, persistence will most affect first responders and clean-up efforts. While persistence must be understood and considered for any chemical-agent release, this thesis assumes that the agent involved in any catastrophe will persist for the duration of analysis. Furthermore, since the analysis covers a short period of time following a catastrophe, it assumes that the size and shape of the contaminated area stays constant.

2. Nerve Agents

Nerve agents cause several violent physiological actions. When inhaled, ingested, or absorbed into the body through the skin or mucous membranes, these agents inhibit enzymes throughout the body, disturbing nerve-signal transmission. Major effects may include: muscle stimulation with uncontrolled contractions followed by fatigue and usually paralysis, tightness in the chest, vomiting and diarrhea, secretions from air passageways, and convulsions or disturbances in the brain leading to death (Department of the Army 1990). The two main nerve agents used in U.S. chemical weapons are the G-agent GB, and the V-agent VX. These nerve agents all exist normally as viscous liquids. G-agents are more volatile, persisting only up to two days, whereas V-agents can persist as long as 16 weeks (DTRA 2001).

GB is a colorless, odorless liquid. The initial vapor threat from GB exposure is the greatest threat. The volatility of GB is an important physical factor as small droplets sprayed from a plane or released from an exploding shell may vaporize and never hit the

ground (Department of the Army 1990). While GB vapor is lethal, it is less persistent than its liquid form, and does not condense on surfaces to become a contact threat. G-agents like GB do not persist for long periods as they decompose either naturally or with chemical neutralization techniques. GB does mix with water easily, can contaminate water sources and can be spread through those sources. However, contamination of water sources does not come into play in this thesis.

V-agents have low volatility and thus high persistence. VX is an oily, odorless liquid that does not vaporize easily, so it is mainly a liquid contact threat. Exposure can take place when a droplet of spray contacts a person's clothing or skin, or when a person touches a contaminated surface. VX does not spread easily on surfaces and does not mix well with water. VX by inhalation is approximately twice as toxic as GB by inhalation, but is up to 100 times more toxic through contact (Department of the Army 1990).

3. Blister Agents

Blister agents, also known as vesicants, are easily absorbed by the human body. These agents cause inflammation, blisters, and general destruction of moist tissues, especially eyes, mucous membranes, and the respiratory tract (Department of the Army 1990). All blister agents are strongly persistent, surviving up to eight weeks. They are normally employed as colorless gases and liquids (DTRA 2001). U.S. blister agents are of the mustard form, primarily Levinstein Mustard (H), Distilled Mustard (HD), and Mustard-T Mixture (HT).

B. U.S. CHEMICAL WARFARE STOCKPILE

CFs at eight Continental United States (CONUS) locations and one overseas location have stored and maintained the inventory of U.S. chemical weapons. These locations are depicted in Figure 1.

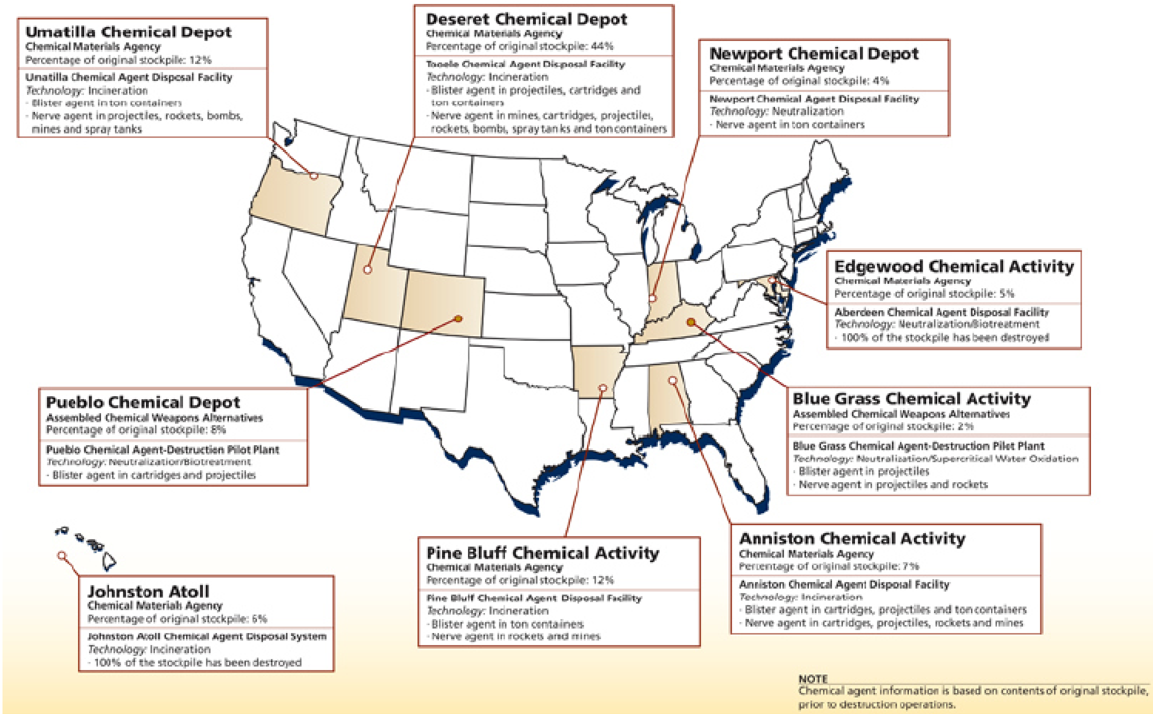

Figure 1. U.S. Chemical Warfare Stockpile Locations (Source: CMA 2007)

On 29 April 1997, the United States agreed to the Chemical Weapons Convention and, in agreement with this convention, began the process of destroying all the chemical-weapons, chemical-agent inventories, and production facilities (CMA 2007a). By December 2000, all the chemical weapons on the Johnston Atoll had been destroyed (CMA 2007a). In March 2006, the first U.S. CF, at the Edgewood Area of Aberdeen Proving Grounds in Maryland, completed destruction of its chemical-agent stockpile, which consisted of mustard agents (CMA 2007a). As of May 2007, with Johnson Atoll and Edgewood destruction complete and other efforts underway, more than 44 percent of the entire U.S. chemical-weapons stockpile had been destroyed (CMA 2007a).

Because agent destruction is nearing completion at the Pine Bluff Chemical Activity in Arkansas, that CF will only receive an operational summary in this thesis. The remaining six CFs comprise candidates for analysis. The following operational-environment assessment for the seven CFs outlines the composition of their chemical-agent stockpiles and provides other background information.

1. Pine Bluff Chemical Activity, Pine Bluff, Arkansas

The Pine Bluff Arsenal (PBA) began storing chemical weapons in 1945. Pine Bluff Chemical Activity, part of the PBA, is located north of Pine Bluff, Arkansas on the Arkansas River; see Figure 2. Little Rock, Arkansas lies 30 miles north of the PBA. The chemical weapons stored at Pine Bluff Chemical Activity consist of various munitions and one-ton containers containing GB or VX nerve agents, or HD blister agent (U.S. Army 2007c). Disposal of these agents began in 2005 and, as of 19 May 2007, all 90,409 GB nerve-agent rockets had been destroyed. Destruction of VX rockets is scheduled to begin in late 2007 (CMA 2007e). To date, 12 percent of the stockpile at Pine Bluff has been destroyed and the remaining stockpile should be destroyed by late 2008 (Department of the Army 2006).

Figure 2. Pine Bluff Arsenal, Arkansas (Source: Google Maps 2007).

2. Newport Chemical Depot, Newport, Indiana

The Newport Chemical Depot, lies southwest of Newport, Indiana, on the west-central border of Indiana, about 60 miles west of Indianapolis; see Figure 3. This CF

opened in 1941 and produced various warfare materials, including chemical agents, through the late 1960s. Since that time, it has stored the liquid chemical agent VX in large steel containers. Agent-destruction operations began in 2005 and, as of 15 May 2007, workers had destroyed approximately 156,126 gallons of liquid VX, amounting to about 52 percent of the original agent stockpile (CMA 2007d).

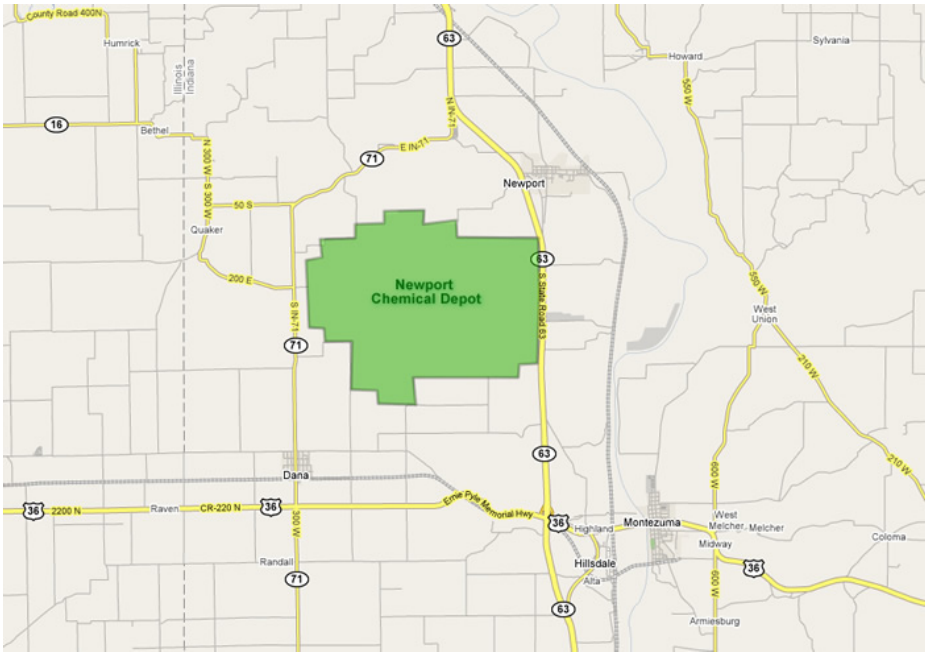

Figure 3. Newport Chemical Depot, Indiana (Source: Google Maps 2007).

3. Anniston Chemical Activity, Anniston, Alabama

The Anniston Army Depot, located west of Anniston, Alabama, was established in 1941; see Figure 4. Beginning in the 1960s, the Anniston Chemical Activity began maintenance and storage of chemical weapons at the Depot. The Anniston Chemical Activity has stored various munitions and chemical agents containing GB or VX nerve agents or HD blister agent (U.S. Army 2007a).

The Anniston Chemical Agent Disposal Facility began construction in 2001, and began destroying chemical weapons in 2003. By March 2006, 142,428 GB munitions and 96,246 gallons of GB nerve agent had been destroyed; no GB agent remains (CMA

2007c). After completing the destruction of GB agent, destruction of VX-filled rockets began. As of March 2007, all 35,662 VX-filled rockets and 41,056 gallons of VX had been destroyed (CMA 2007c). Destruction operations will next process VX-filled artillery shells. Overall, 27 percent of the chemical weapons stockpile at Anniston Chemical Activity had been destroyed as of May 2007 (U.S. Army 2007a). The projected date to complete all operations is early 2012 (Department of the Army 2006).

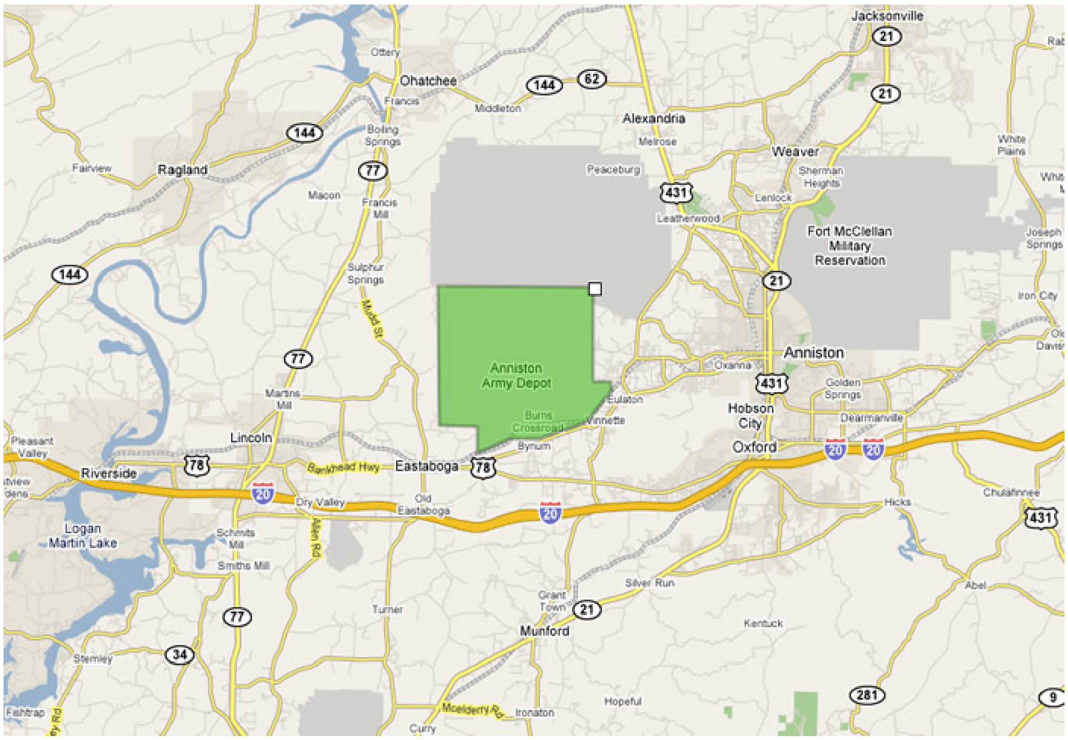

Figure 4. Anniston Army Depot, Alabama (Source: Google Maps 2007).

4. Blue Grass Chemical Activity, Richmond, Kentucky

The Blue Grass Army Depot, located near Richmond, Kentucky, houses the Blue Grass Chemical Activity; see Figure 5. The Army has stored chemical weapons at this facility since 1944. Located to the southwest of Richmond and 20 miles south of Lexington, Kentucky, the Blue Grass Chemical Activity currently stores 523 tons of chemical agents: blister agent in projectiles and nerve agents in projectiles and rockets (Blue Grass Chemical Stockpile Outreach Office 2006). In 2003, a contract was awarded

to design, construct, and operate a facility to destroy the stockpile at Blue Grass. As of May 2007, destruction of chemical agents has not yet begun.

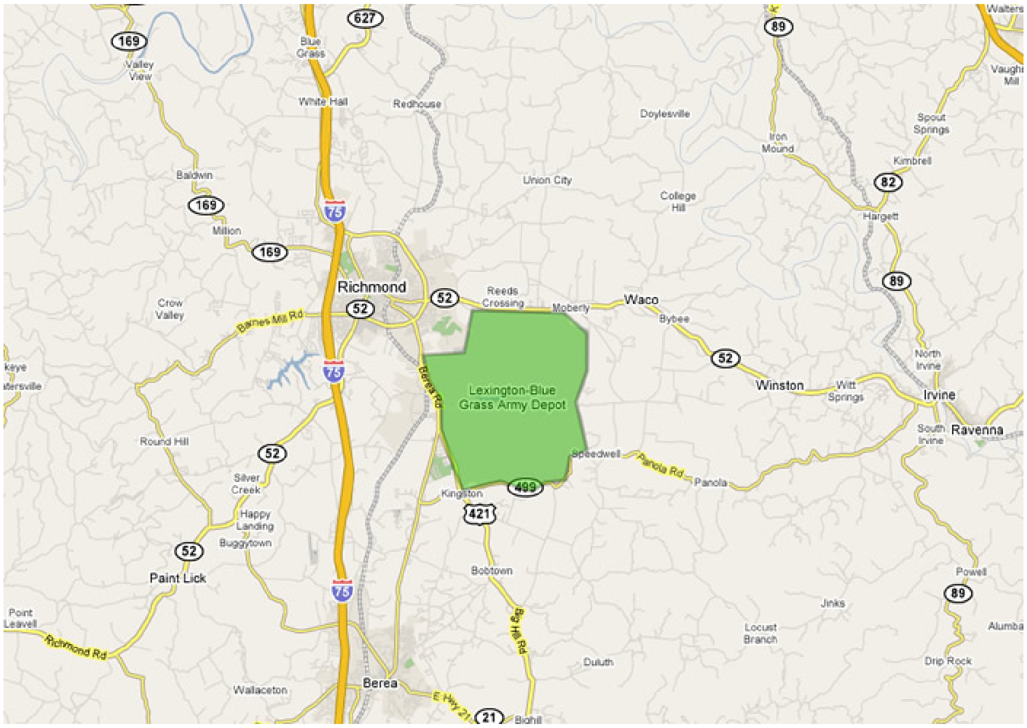

Figure 5. Blue Grass Army Depot, Kentucky (Source: Google Maps 2007).

5. Pueblo Chemical Depot, Pueblo, Colorado

The Pueblo Chemical Depot, located east of Pueblo, Colorado, began storing chemical weapons during the 1950s; see Figure 6. The nearest major city, Colorado Springs, lies 40 miles to the northwest of the storage facilities. The Pueblo Chemical Depot houses a large stockpile of chemical weapons, including 2,611 tons of weapons with mustard (HD) agent (Pueblo Chemical Agent-Destruction Pilot Plant 2006). The chemical weapons stored include artillery and mortar shells filled with mustard agent. In 2002, a contract was awarded to design, construct, and operate a facility to destroy the munitions store at the facility. As of May 2007, destruction of chemical agents had not yet begun.

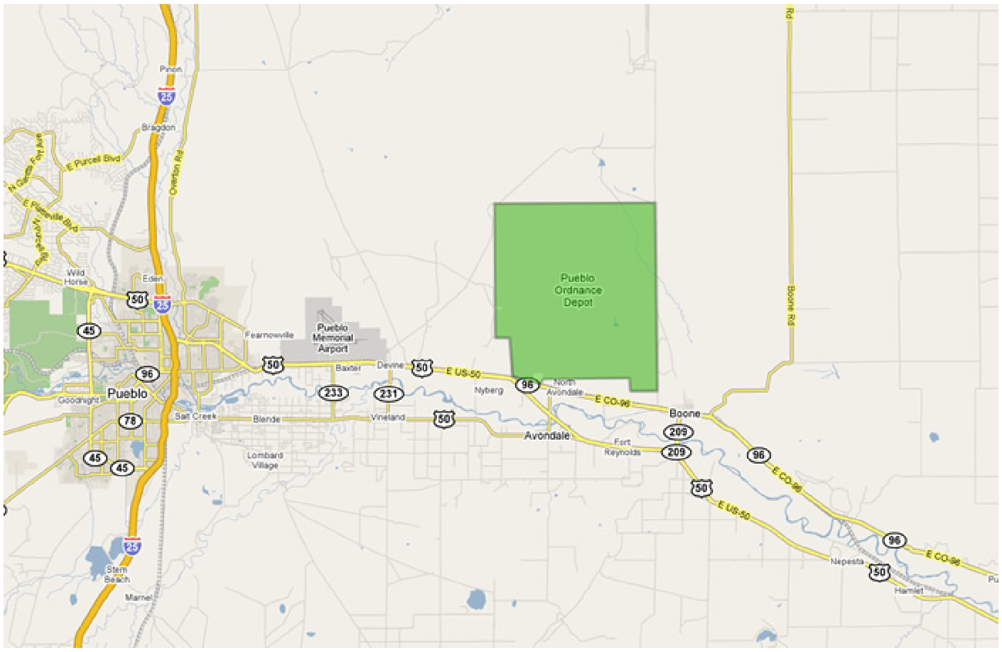

Figure 6. Pueblo Chemical Depot, Colorado (Source: Google Maps 2007).

6. Deseret Chemical Depot, Tooele, Utah

The Deseret Chemical Depot, lies 30 miles southwest of Salt Lake City, Utah, just south of Tooele, Utah; see Figure 7. The Army has stored almost 45 percent of the nation's chemical weapons at the Deseret Chemical Depot since 1942 (U.S. Army 2007f). The Depot stores various chemical munitions and containers containing GB and VX nerve agents or H, HD, and HT blister agent (U.S. Army 2007d).

The Tooele Chemical Agent Disposal Facility completed construction in 1993, and began destroying chemical agents in 1996. As of 1 May 2007, all of the Facility's munitions containing GB nerve agent had been destroyed, and 1209 mustard-agent-filled one-ton containers had also been destroyed. The latter quantity represents 17.4 percent of the Depot's original mustard-agent stockpile (CMA, 2007a). Overall, nearly 62 percent of the chemical agents at the Deseret Chemical Depot had been destroyed by the specified date.

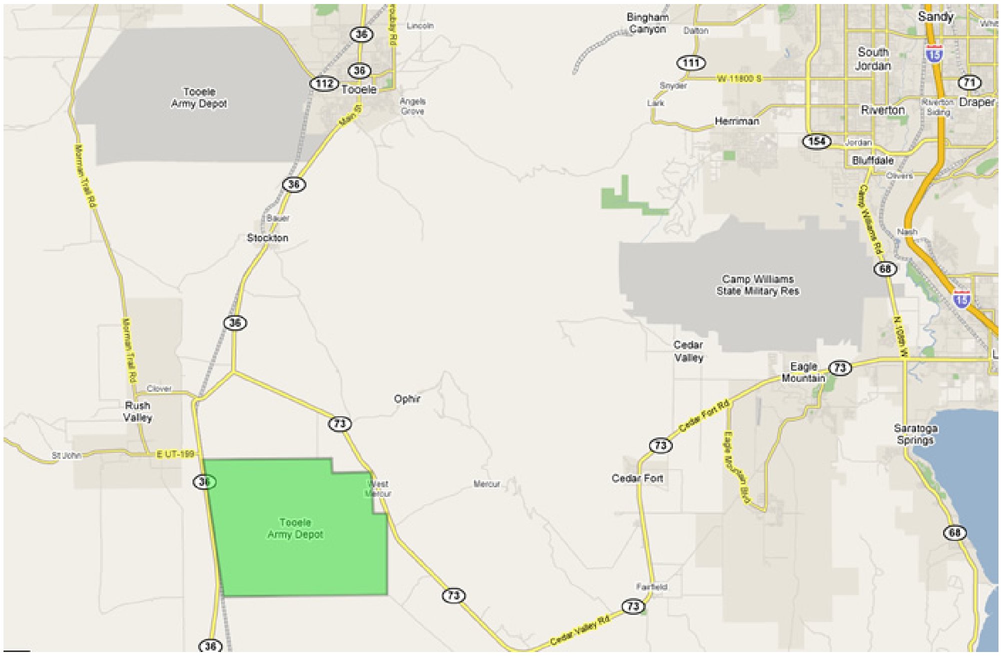

Figure 7. Tooele Army Depot, Utah (Source: Google Maps 2007).

7. Umatilla Chemical Depot, Umatilla, Oregon

The Umatilla Chemical Depot lies six miles southwest of Umatilla, Oregon, and west of the larger city of Hermiston; see Figure 8. On the north-central border of Oregon with Washington, the Depot is situated near the Columbia River and about 25 miles southwest of Kennewick, Washington. The Umatilla Chemical Depot opened in 1941 and began storing chemical weapons in 1962. The Depot stores various munitions and containers containing GB or VX nerve agents or HD blister agent.

The Umatilla Chemical Agent Disposal Facility completed construction in 2001 and began destroying chemical weapons in 2004. As of 17 May 2007, the facility had destroyed 139,393 chemical munitions and 962 tons of GB chemical agent, totaling nearly 26 percent of all the chemical agents at the Depot (CMA, 2007f). The projected date to complete all operations is early 2011 (Department of the Army 2006).

Figure 8. Umatilla Chemical Depot, Oregon (Source: Google Maps 2007).

C. INFRASTRUCTURE

Several major infrastructure systems surrounding any CF may be affected by chemical agents. This thesis focuses on road, public-health, and emergency-response systems. Additional infrastructure systems that may be impacted in a chemical catastrophe include Department of Defense (DoD) facilities, railroad networks, energy systems and services, water systems, and agriculture. These other infrastructure systems are not directly relevant to the thesis, but they are discussed here for completeness and in consideration of future work. Other infrastructure systems, such as banking and finance, commercial industries, information and telecommunications, are not considered to be significantly impacted due to the relatively rural locations of the CFs. Although no specific data identify effects to the infrastructure, the following paragraphs summarize the likely effects and results, as suggested by the author, following a chemical catastrophe.

1. Road Network

A large portion of the road network near a CF, including major traffic arteries, can become unusable in the event of a chemical catastrophe. The loss of these roads can impact all of the other infrastructure systems because those systems, or key parts of them, may become inaccessible. For example, cellular telephone towers and electric power substations might need repair, but become inaccessible and remain out of service. Except for population evacuation, roads will be unusable until they have been decontaminated, either through natural degradation or through active neutralization by clean-up crews. Until roads are clear for use, transportation and emergency services will have to reroute around the contaminated area, and certain services may not have access to isolated areas. For example, ambulances may be unable to reach injured persons because certain roads are unusable.

2. Public Health

Protecting the local population from chemical agents is a significant issue for any CF. In the event of a chemical catastrophe, local residents may be exposed, injured, and even killed. The ability to evacuate and treat the public surrounding a CF must be considered. Health services will degrade or even close down if healthcare facilities and emergency-responders fall within the contamination area and can no longer operate. Additionally, treating the population for normal health issues will become more complicated for a degraded emergency-response system.

3. Emergency-Response Systems

Local emergency-response systems, which include first-response capabilities and treatment facilities, may be lost or incapacitated during a chemical-catastrophe event. First responders, such as firefighters, ambulances, and police will be constrained by the contaminated area and may not be able to reach key population centers and casualties. If local services are blocked from reaching casualty areas, outside agencies will need to

respond or alternate access methods will be required, e.g., helicopter or watercraft. These emergency-response systems will be modeled in this thesis to determine vulnerable population areas.

4. Department of Defense (DoD) Facilities

Because each CF is located on a military installation, a chemical catastrophe will impact all operations at the installation. Each installation has plans to respond to such an event. Most CF installations have few tenant operations, so the impact to other military functions will be limited.

5. Railroad Network

All of the CFs have railroads lines located nearby. A contaminated railroad line will not be usable until decontamination is verified. By examining railroad maps near CFs, it appears that the impact to rail transportation scheduled to transit a potentially affected area will be minimal, as most rail traffic can be rerouted around the area. Increases to time and fuel will not be significant because of the small increase in overall route lengths. However, deliveries to the area near the CF will be completely stopped if rail yard facilities are contaminated.

6. Energy Systems and Services

Chemical agents should not have a direct impact on energy-supply systems such as generation facilities, gas and oil pipelines, and power lines. However, personnel required to run, maintain, and repair systems may not be able to reach contaminated systems due to road-network contamination.

7. Water Systems

Local water systems directly contaminated by chemical agents will be a major concern in a chemical catastrophe. Although water promotes hydrolysis of agents which

reduces their effectiveness, it does not neutralize them, so contaminated water will be unusable (DTRA 2001). Contaminated water will also be hazardous to wildlife and agricultural areas.

8. Agriculture

Chemical agents will affect livestock and crops in the contaminated area. Animals will experience the same effects as humans and will suffer casualties. In fact, animal casualties may help map the extent of the chemical-agent contamination. Agricultural crops, like all vegetation, will absorb chemical agents and increase agent persistence.

D. CHEMICAL CATASTROPHE

How each infrastructure system is impacted will be a function of the chemical catastrophe, more specifically, its parameters: the agent involved, quantity of agent released, weather conditions, etc. The specific details of how and why a chemical catastrophe occurs are beyond the scope of this thesis; the thesis simply assumes that a chemical catastrophe, with hypothetical parameters selected, has taken place at a specific CF. The geographical extent of the catastrophe is computed for the set of parameters using a well-established dispersion model implemented in the HPAC software (DTRA 2004). MINO then determines which infrastructure components and systems are affected.

The Defense Threat Reduction Agency (DTRA) uses the Hazard Prediction and Assessment Capability (HPAC) software for predicting chemical dispersion. This thesis generates the chemical-catastrophe scenarios with it, for analysis. HPAC predicts the effects of hazardous-material releases into the atmosphere and collateral effects on civilian and military populations (DTRA 2007). Appendix A describes the HPAC model.

Results from HPAC depend on user-specified weather conditions and, in turn, those significantly impact results from MINO. Other than wind, the weather settings displayed in Table 1 are used in HPAC for all computational tests for all CFs. The primary wind directions and speeds for each CF scenario come from historical climatic

wind data from a 66-year period from 1930-1996, published by the National Climatic Data Center, National Oceanic and Atmospheric Administration (NOAA) (NOAA NCDC 1996). In addition to these base cases with historical prevailing wind directions, other HPAC runs with different wind directions will be run to examine other, perhaps more devastating scenarios.

Weather Parameter	HPAC Setting (Fixed)	Other Possible Settings
Cloud Cover	Broken	Clear, Scattered, Overcast
Surface Moisture	Normal	Dry, Wet
Precipitation	None (0.00 mm/hr)	From Light Rain to Heavy Snow

Table 1. HPAC Weather Settings for Computational Tests

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III. MODEL DEVELOPMENT

Following a catastrophe, a cascade of events will take place, some planned and others not. In the case of a wide-spread chemical-agent release, a large portion of the local population will evacuate. In fact, authorities will require at least part of that evacuation. With a large-scale evacuation, certain segments of the road network may experience high traffic volumes, which will slow the evacuation and increase exposure risk to evacuees. The first contingency-response model described in this chapter examines this problem and helps identify the likely routes and traffic intensities for evacuation planning.

The emergency-response system should also expect a spike in activity. Not only will people need treatment for chemical-agent exposure, but an evacuation, potential wide-spread panic, and a heavily loaded road system will all degrade the emergency-response system's performance. The second contingency-response model described in this chapter captures part of this problem by determining how emergency-response distances change across the study because of unusable roads and ERS locations.

A. POPULATION, ROAD, EMERGENCY REPONSE SYSTEM MODEL

For this thesis, the infrastructure network G^{MINO} represents an interconnected network of roads, population, and emergency services. This undirected network, $G^{MINO} = (N, A)$, is defined by:

<u>Nodes *N* with subsets</u>

- N^P representing population aggregations,
- N^E representing locations for emergency-response units,
- N^R representing road intersections, $(N^R = N - N^P - N^E)$, and

<u>Arcs *A* with subsets</u>

- A^{PR} representing connections of population nodes to road intersections $(A^{PR} \subseteq N^P \times N^R)$,
- A^{RR} representing actual road segments between intersections, $(A^{RR} \subseteq N^R \times N^R)$

A^{ER} representing connections of emergency-response units to road intersections ($A^{ER} \subseteq N^E \times N^R$), and

Numerical data to be described later.

Constructing G^{MINO} requires accurate critical-infrastructure (CI) data. The CI data is extracted from various unclassified datasets and then merged, using a common reference system: MINO uses latitude and longitude coordinates. The construction process first defines the road-network infrastructure and then integrates the emergency-response infrastructure, which includes the hospitals and first responders. Population groups must also be represented and connected to the road network. The following sections outline this process; appendix B contains more detail.

Road and population data are taken from the 2000 Census TIGER database (Topologically Integrated Geographic Encoding and Referencing database) available to the public (ESRI 2007). Each road segment from the database, for the study area, will correspond to an arc in A^{RR}. The union of arc endpoints over all arcs in A^{RR} forms the set of nodes N^R. The database contains much additional data, but the only additional data extracted are arc lengths, road names, and road types.

Next, the human population is modeled and connected to the road network. From the TIGER database, census population data is provided for small geographical areas, referred to as "blocks." A population node $i \in N^P$ will represent each census block population as a point geographically centered in the census block. Some blocks contain no population and nodes are not created for these; population nodes containing five or fewer people are paired with neighboring, larger population nodes for simplicity.

The final set of population nodes is then connected to the road network. For each node $i \in N^R$, a search procedure finds the two closest road nodes $j_1(i), j_2(i) \in N^R$, and arcs $(i, j_1(i))$ and $(i, j_1(i))$ are created. The union of all such arcs is A^{PR}. To ensure these artificial arcs are not used for transit, other than to get the population onto the road network or to allow emergency responders to reach the population, a large cost or length

C is assigned to each. That is, $c_{ij} = C$ for all $(i, j) \in A^{PR}$. The full set of these arcs is defined by $A^{PR} = \bigcup_{i \in N^P} \{(i, j_1(i)), (i, j_2(i))\}$.

The ERS infrastructure data is provided by NGA from the Homeland Security Infrastructure Program database ("HSIP"; see NGA 2007). From the ERS data, we select locations for two different ERS categories from each CF area. The emergency-responder (ER) category includes Emergency Medical Services (EMS), fire stations, and ambulance providers. The other category, referred to as "hospitals" here, actually includes hospitals and ambulatory surgical facilities. As with population nodes, we attach each ERS node to the road network by two arcs; the collection of all such arcs is A^{ER}. Each arc $(i, j) \in A^{ER}$ has its true length assigned as its modeled length, c_{ij}.

G^{MINO} contains all nodes, arcs and numerical data required for modeling the evacuations and emergency-response problems. Figure 9 displays a geographic map of G^{MINO} extracted from a section of the city of Pueblo, Colorado.

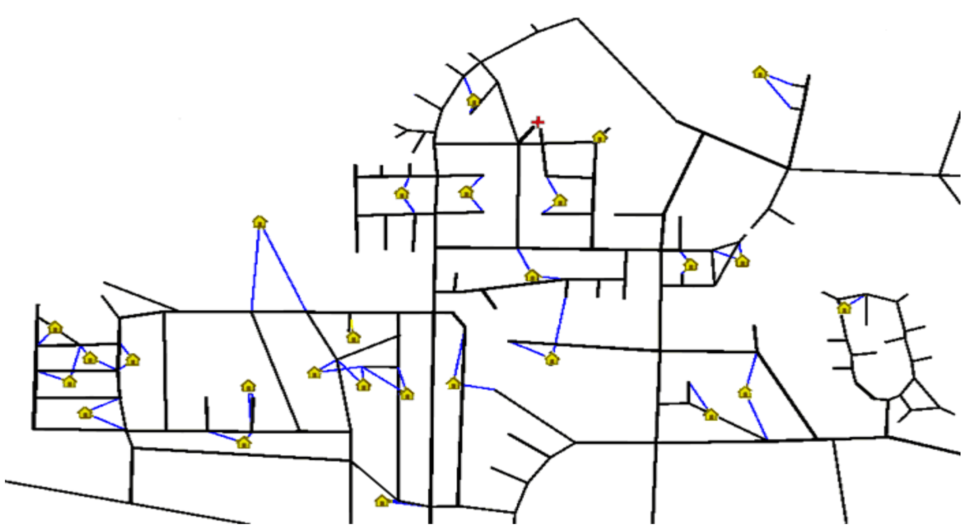

Figure 9. Example of G^{MINO} Extracted from Pueblo, Colorado.
House icons denote population nodes. The blue lines, or lines connecting the house icons, are the artificial arcs connecting the population nodes to road nodes, and correspond to the arc set A^{PR}. The red "+" icon depicts the sole emergency-response node from N^E in this small region; it is connected to the road network by two arcs from A^{ER}. The remaining lines (black in a color reproduction) represent the road arcs contained in the set A^{RR}.

B. CATASTROPHE SCENARIOS

With a complete infrastructure network, an abstract model for a chemical catastrophe is necessary to develop the scenario. A scenario, s, and the application model being applied, simply alter the components in, and data associated with, G^{MINO}.

For each CF, a chemical-catastrophe scenario is run in HPAC based on the chemical agent in inventory, plus weather, terrain, and other factors. Different sets of scenario parameters will cover most likely incidents, and some cover what the author believes may be nearly worst-case incidents. For instance, a scenario using a prevailing wind direction may correspond to a "likely" incident with contamination being spread into lightly populated areas, but if the wind shifts 180 degrees, a heavily populated area could be contaminated in a worst-case incident. Based on the scenario, an area surrounding the chemical facility is identified as the contamination area and effects will be assigned to critical infrastructure in that area and a surrounding buffer zone.

HPAC utilizes plume and chemical-agent dispersal calculations to determine the contamination area. HPAC takes the incident and release information (the combination of "where, what, and when" parameters and the specified environmental data), and predicts where the chemical-agent material will move through the atmosphere, and calculates its deposition on surfaces (DTRA 2004). HPAC's atmospheric transport model is called SCIPUFF. It is a Lagrangian, Gaussian puff model that relates dispersion rates to measurable turbulent velocity statistics. Further detail about SCIPUFF can be found in the HPAC 4.04 Users Manual (DTRA 2004).

HPAC typically generates a roughly elliptical contamination area, referred to hereafter as the "contamination area." Figure 10 shows actual HPAC results for a scenario at the Umatilla Chemical Depot. An ellipse approximates this contamination area, called the "contamination ellipse." Any person remaining in the contamination ellipse is likely to become sick and even die. Since the actual extent of chemical-agent contamination cannot be mapped precisely, a buffer zone is added to the model's contamination ellipse. This buffer zone may be viewed as representing uncertainty in prediction, and (a) the fact that the local populace, fearing for its lives, is likely to

evacuate a large area surrounding the truly contaminated area, and (b) the fact that authorities will naturally build a buffer zone into their evacuation orders. The area defined by the contamination ellipse and added buffer is referred to as the "evacuation ellipse" or "evacuation area." All models assume that the local population must be evacuated from anywhere inside the evacuation area. Individual models will identify nodes within the defined evacuation area to assign appropriate penalties.

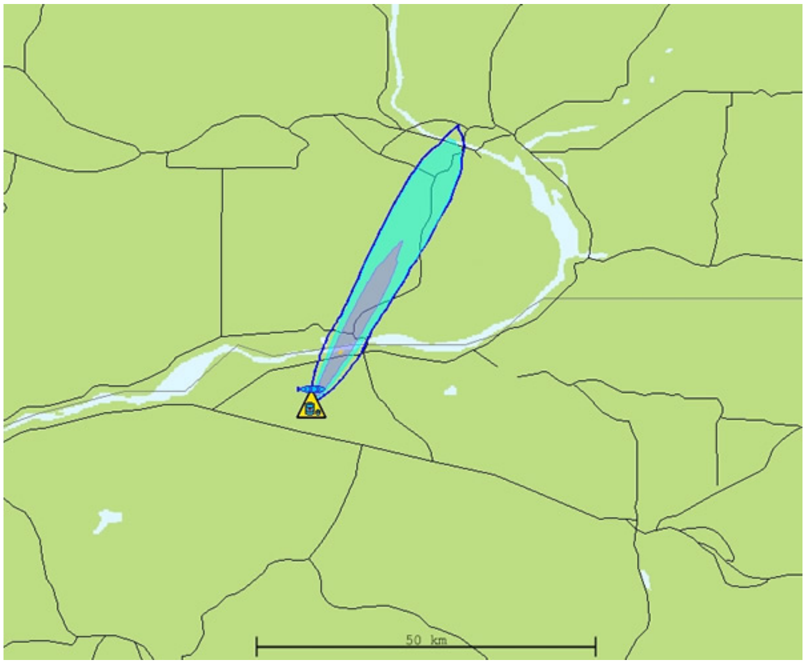

Figure 10. Example HPAC Chemical Catastrophe Result.
This figure shows the contamination area identified by HPAC for a hypothetical scenario at the Umatilla Chemical Depot. The Depot is denoted by a yellow triangle and colored ellipse-like areas represent different casualty levels in HPAC. The contamination area equates to the area within the outer-most blue solid line and is called the "Casualty Possible" area by HPAC (DTRA 2004).

C. MULTI-INFRASTRUCTURE NETWORK OPERATIONS MODEL

With the aforementioned datasets integrated into $MINO_{NET}$, the effects to specific infrastructures will be determined. $MINO_{NET}$ is parameterized for analysis after running the HPAC scenario for a particular scenario. With a parameterized $MINO_{NET}$, a shortest-path algorithm is solved for different contingencies, either population evacuation or

emergency response. Each model is built in Microsoft Excel 2003 and processed using Visual Basic for Applications (VBA) algorithms. The VBA shortest-path algorithms solve quickly, in less than a minute.

1. Creating the Evacuation Ellipse and Parameterizing MINO$_{\text{NET}}$

After running HPAC for a given scenario, the plotted contamination area is exported for approximation as a contamination ellipse. The ellipse approximation simplifies the construction of the larger evacuation ellipse, which is used in evacuation and emergency-response system models.

To generate the contamination ellipse equation, we first plot the contamination area and define the two extreme ends of that elongated area as the end points for the semimajor axis. The area center (x_c, y_c) is calculated by averaging the two end points. The angle of rotation φ is also computed from the chord connecting the two end points. This center point is used to translate the contamination area and the angle φ is used to rotate the area on axis. With the area centered at the origin, the ellipse's semimajor and semiminor axes are then measured; their lengths are denoted a and b, respectively. The center point (x_c, y_c) and angle φ are recorded for use in the search functions.

Next, the contamination ellipse is expanded into the evacuation ellipse based on two user-specified parameters. The "width-expansion parameter," w_{EF}, increases the width of the semiminor axis by its value. The thesis arbitrarily uses $w_{EF} = 4$ throughout; other users of MINO will want to explore different values. The "range-expansion factor," r_{EF}, increases the length of the semimajor axis; tests in this thesis set $r_{EF} = 1.1$. This small value is used primarily to limit the size of MINO$_{\text{NET}}$. (Larger increases to r_{EF} may expand this network model beyond current software limitations.) The evacuation ellipse, translated and rotated, is thus defined by

$$\text{All coordinates } (x, y) \text{ such that } \frac{x^2}{(r_{EF}\, a)^2} + \frac{y^2}{(w_{EF}\, b)^2} \le 1 .$$

In terms of the original coordinate system then, the evacuation ellipse is defined by:

All coordinates (x, y) such that

$$\frac{[(x-x_c)\cos\varphi+(y-y_c)\sin\varphi]^2}{(r_{EF}\ a)^2}+\frac{[(y-y_c)\cos\varphi-(x-x_c)\sin\varphi]^2}{(w_{EF}\ b)^2}\le 1\,.$$

$\mathrm{MINO}_{\mathrm{EVAC}}$ only marks population groups within the evacuation ellipse, whereas $\mathrm{MINO}_{\mathrm{ERS}}$ marks all population groups and ERS locations, and assigns penalties to road arcs within the evacuation ellipse. For population and ERS nodes, a simple binary value indicates if the node is inside the evacuation ellipse or not. For road arcs in $\mathrm{MINO}_{\mathrm{ERS}}$, a search function looks at both nodes associated with the arc. If either is within the evacuation ellipse, the road is considered unusable and the penalty C is added. Specifically, for each $(i, j)\in A^{RR}$, if either i or j is within the evacuation area, then the nominal length of the arc, which is c_{ij}, becomes $c_{ij}+C$.

After integrating the chemical-catastrophe data into $\mathrm{MINO}_{\mathrm{NET}}$, that infrastructure model is applied to the evacuation model $\mathrm{MINO}_{\mathrm{EVAC}}$, and the emergency-response model $\mathrm{MINO}_{\mathrm{ERS}}$. The next two sections describe this process.

2. The Evacuation Model

After a chemical catastrophe, all population within the evacuation ellipse will depart for safety, or at least attempt to depart. $\mathrm{MINO}_{\mathrm{EVAC}}$ models this situation with $G^{EVAC}=(N^P\cup N^R,\ A^{PR}\cup A^{RR})$. Also, the set of population nodes, N^P, is divided into two sets: the set of "unsafe" nodes that are inside the evacuation ellipse and must be evacuated and those which are deemed "safe" and do not require evacuation.

In $\mathrm{MINO}_{\mathrm{EVAC}}$, all n_p persons in each population group p within the evacuation area, are assumed to evacuate that area by following the same shortest route to the closest safe node. By solving a single shortest-path problem as described below, it is possible to identify the evacuation paths Q_{ps} which each population group p will use in scenario s. The traffic intensity v_{rs}, for each road segment r in scenario s, is computed as $v_{rs}=\sum_{p|r\in Q_{ps}} n_p$.

It would seem necessary to solve a shortest-path problem for each population group p within the evacuation ellipse. This can be avoided, however, by solving a "reverse shortest-path problem" with unsafe nodes as sinks, and safe nodes as sources. A single shortest-path calculation then identifies the shortest route for each population group, corresponding to a single node, to reach its nearest exit from the evacuation ellipse. It is assumed that all persons within a population group follow the same shortest path, and thus it is easy to compute the number of persons traversing a given roadway.

A label-correcting algorithm, implemented with a deque (double-ended queue), solves the shortest-path problem (Ahuju, Magnanti and Orlin 1993, p. 143). The algorithm is modified to handle multiple sources by setting the distance label for each source node to 0, and placing each such node on the deque before beginning distance updates for the rest of the nodes. It is then a simple matter to use the optimal predecessor function, along with population values, to compute traffic intensities v_{rs}.

The evacuation model estimates traffic intensities for road segments used to evacuate the evacuation area. Identifying the most used paths, i.e., those paths with the greatest amount of population movement, will help provide insight into which roads will be heavily used and potentially cause traffic problems during the evacuation. Results will also show which safe areas will need to absorb the largest numbers of evacuees.

3. The Emergency-Response System Model

We create two variants of the ERS model, MINO_{ERS}. The first, $\text{MINO}_{\text{ERS1}}$ helps identify where the local population may have difficulty in reaching a hospital facility after the chemical catastrophe. The second, $\text{MINO}_{\text{ERS2}}$, determines if safe population nodes can be reached by emergency responders. In both variants, the model identifies isolated population nodes that might require access by means of alternate transportation (e.g., helicopter) or by non-local emergency-response units. Both variants also identify travel-distance increases between population groups and respective emergency services. By mapping population nodes with significantly increased distances, emergency-response planners can identify vulnerable areas.

MINO$_{ERS}$ uses G^{RESP} to represents the post-catastrophe network for evaluating changes in emergency response. This graph is defined by

$G^{RESP} = (N_R \cup N_{P_{SAFE}} \cup N_{E_{SAFE}}, A)$

where

$N_{P_{SAFE}}$ = All nodes $i \in N^P$ outside the evacuation ellipse, and

$N_{E_{SAFE}}$ = All nodes $i \in N^E$ outside the evacuation ellipse

Prior to the parameterization of MINO$_{NET}$, using the basic G^{MINO}, one shortest-path solution from MINO$_{ERS1}$ identifies baseline shortest paths from each population node to the closest hospital facility. Another solution, from MINO$_{ERS2}$, identifies the baseline shortest paths from each population node to the nearest emergency responder. The baseline shortest-path distances for each population group p are denoted d_p^{H0} and d_p^{E0} for hospital and emergency responders, respectively. After the baseline distances are calculated, each road arc within the evacuation area is assigned a penalty to inhibit travel through the evacuation area, as described earlier. The model next recalculates shortest paths using G^{RESP} for the hospital facilities and emergency responders, calculating post-catastrophe distances, d_p^{H1} and d_p^{E1}, to compare to baseline distances. Specifically, the differences $d_p^{H1} - d_p^{H0}$ and $d_p^{E1} - d_p^{E0}$ will be evaluated for safe population groups p.

We solve these shortest-path problems using the same algorithm as used for MINO$_{EVAC}$. The algorithm is implemented almost identically to the evacuation model algorithm and executes twice, once for hospitals, MINO$_{ERS1}$, and once for emergency responders, MINO$_{ERS2}$.

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IV. MODEL SCENARIOS, ANALYSES AND RESULTS

This chapter describes the development of MINO for each CF, details on the chemical-catastrophe scenarios examined, and results from the evacuation and ERS models for those scenarios. Following presentation of analytical results, a short summary for each CF characterizes potential vulnerabilities to the local population and infrastructures for the scenarios analyzed. These scenarios represent hypothetical situations and as a reminder, only a few specific scenarios are examined for each location, and they represent only a small fraction of the possible scenarios that could occur.

The discussion in Chapter 2, Section D applies for all CFs, and that discussion is not repeated here. For reasons noted earlier, no summary is included for the Pine Bluff Chemical Activity. As explained later, the Deseret Chemical Depot is not fully analyzed because of software limitations. Google Earth and Keyhole Markup Language (KML) are used to display MINO results; see Appendix C for details.

A. ROAD TRAFFIC RESULTS FROM $\text{MINO}_{\text{EVAC}}$

To relate road-traffic results from $\text{MINO}_{\text{EVAC}}$ to an expected roadway congestion level, a "traffic-intensity scale" is developed here to help estimate traffic speeds in an evacuation. A slow evacuation will increase the potential for additional contamination of the population and cause more casualties. For simplicity, the following assumptions are made: each vehicle contains 2.0 persons, traffic travels on two out-bound freeway lanes, and the evacuation transpires in a two-hour window. (No further attempt has been made to incorporate actual road capacity, additional roads, etc.) With these assumptions, interpolations can be made from the 2005 Urban Mobility Report's Freeway Speed Estimation Curves (Schrank and Lomax 2005) to create Table 2.

Traffic Intensity (Persons)	Evacuation Speed (mph)
Up to 3,750	60 mph (minimal impact)
5,000	50 mph
5,500	40 mph
6,000	30 mph
7,500	20 mph

Table 2. Road Traffic-Intensity Scale

This table provides a rough guide to gauge road-traffic results. Table 2 implies that when traffic intensities reach or exceed 5,000 persons, traffic congestion may become a problem. (This happens in scenarios for the Anniston, Blue Grass, Pueblo, and Umatilla locations.) However, much more study is needed on this topic and the discussion of results does not try to point out congested roads. The terms “high-intensity traffic” and “medium-intensity traffic” will describe results, but these are only relative to other traffic intensities in the scenario.

B. NEWPORT CHEMICAL DEPOT, INDIANA

1. Parameters and Data Processing (Newport)

For the Newport Chemical Depot, MINO defines an area roughly 60 miles wide (east to west) and 60 miles tall (from north to south). The entire network model includes 57,731 road segments, 8,360 population nodes encompassing 282,567 people, and 154 emergency-response system locations. (Recall that these locations include hospitals, surgical facilities, EMS, fire stations, and ambulance providers.)

NOAA historical wind data does not cover Newport, Indiana, so the wind data used in this test comes from the nearest cities for which NOAA data is available, Indianapolis, Columbus, and Springfield, Illinois. Indianapolis is the nearest city, and the dominant prevailing wind there is southwest (SW) at 7-11 miles per hour (mph) (NOAA NCDC 1998). Consequently that wind direction and speed is assumed for one scenario. Since the other two nearby cities both have a dominant prevailing south (S) wind at 7-13 mph, a south wind is used for a second scenario.

The Newport Chemical Depot chemical catastrophes are centered at location 39.854N, 87.431W. Table 3 displays parameters used in HPAC to generate the two scenarios for this Depot. The construction type “bermed” refers to a concrete, reinforced bunker with a mound or earth barrier.

HPAC Settings	Level	Winds	Type
Agent	VX (Nerve)	1. SW (225 degrees) @ 10 mph	Prevailing
Facility Type	Storage Containers	2. S (180 degrees) @ 10 mph	Prevailing
Construction	Bermed		
Weapon Size	500 lbs		

Table 3. Newport Chemical Depot Scenario Parameters.

Figure 11 shows the contamination areas calculated by HPAC for the two scenarios. For analysis, each contamination area is then approximated as an ellipse, and that ellipse is enlarged to create the “evacuation ellipse,” as described in Chapter III, Section C. (Figure 12 shows the two ellipses for the first scenario, and Figure 13 shows the ellipses for the second scenario.)

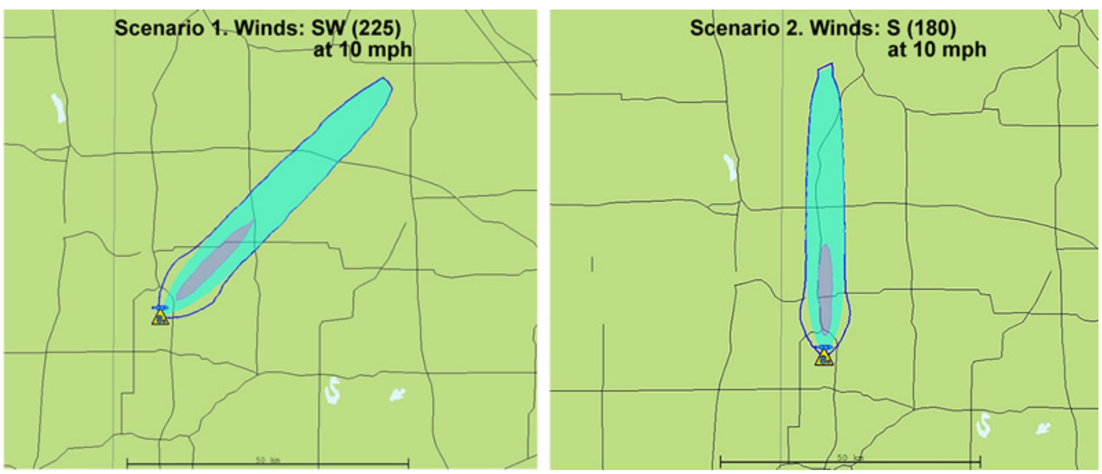

Figure 11. Newport Chemical Depot Chemical Catastrophes.
Figures show contamination areas for two different scenarios.

2. Analysis and Results (Newport)

The first catastrophe scenario (SW wind at 10 mph) for Newport results in a large evacuation ellipse that covers 1,043 population nodes, totaling 23,471.

Figure 12 depicts the resulting MINO$_{EVAC}$ network with roads, contamination ellipse, evacuation area, and highlighted high-traffic roads.

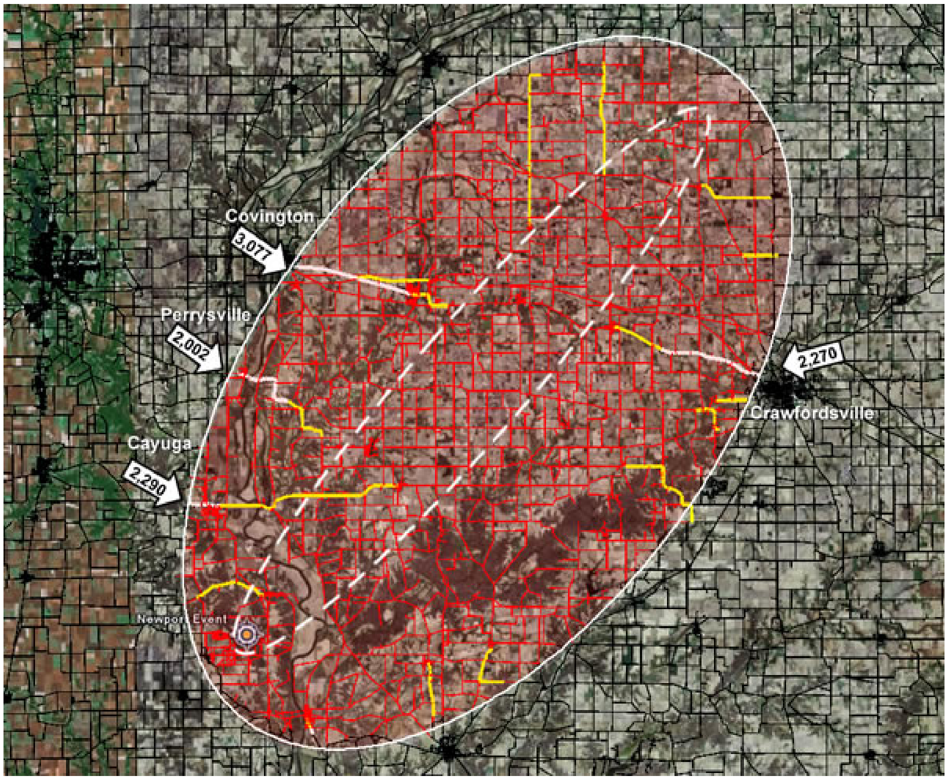

Figure 12. Newport Chemical Depot Evacuation Result (Scen. 1: SW Wind)
Key (for this and similar figures to follow): The incident location is the compass-like icon in the lower left; the black lines represent road segments; the dashed ellipse is the contamination ellipse; and the red area/lines (inside the largest ellipse) highlight the evacuation area. For MINO$_{EVAC}$ results: the roads with high-traffic intensity are bold white lines, and have arrows (or small ovals in other figures) indicating their locations with the calculated number of persons traveling out of the evacuation area at this locale. The highlighted roads without arrows (yellow in a color reproduction, white in black-and-white) define the roads with medium-intensity traffic.

With no major cities in the evacuation area and a rather dense road network, traffic levels are low along shortest-path routes, reaching a maximum of just 3,077 persons on U.S. Highway 136. Table 4 lists the resulting high-intensity traffic and medium-intensity traffic roads. In addition to mapping the roads listed in Table 4, Figure 12 maps roads with medium-intensity traffic having intensity greater than 400 persons per road.

High-Intensity Traffic Roads		Medium-Intensity Traffic Roads	
Road Name	Persons	Road Name	Persons
U.S. Highway 136 (W)	3077	Bunkertown	1165
State Road 234	2290	Coffing Brothers	1165
Waynetown (U.S. 136)	2270	South County Line	1154
State Road 32	2002	B	1130
Bridge	1301	County Road 670	1041
Canal	1301	Stringtown	1009
County Road 550	1301	McGinty	1005

Table 4. Newport Road Traffic (Scenario 1: SW wind, 10 mph)

The evacuating population around Newport increases population numbers in a few safe locations, as highlighted in Figure 12. These locations are likely areas for evacuees to pass through, or to stop and congregate, and measures should be taken to accommodate this. These areas should also anticipate receiving evacuees who have been exposed to the relevant chemical agent. The ability to treat and transport population outside of the evacuation area is examined next, using the two variants of the ERS model.

The Newport area has a well-developed and dense emergency-response system network. Results for the two ERS model variants show minimal changes in response distances for (members of the) population reaching a hospital, and for emergency responders reaching the population. In other words, even though several emergency-response system locations would be contaminated and become unusable, other safe ERS locations are close and could substitute. The reader should note, however:

Caveat 1.

> This ERS analysis does not take into account the capacity of the "substitute" hospitals or contingency plans for augmenting hospital care, and it is possible that some of these could be overwhelmed by needing to treat patients from a larger-than-normal area, in a situation with a large number of casualties.

The second scenario (S wind at 10 mph), creates another large area in which 39,169 persons evacuate from 1,275 population nodes. Although this is a worse evacuation scenario than the previous, results are similar; see Figure 13.

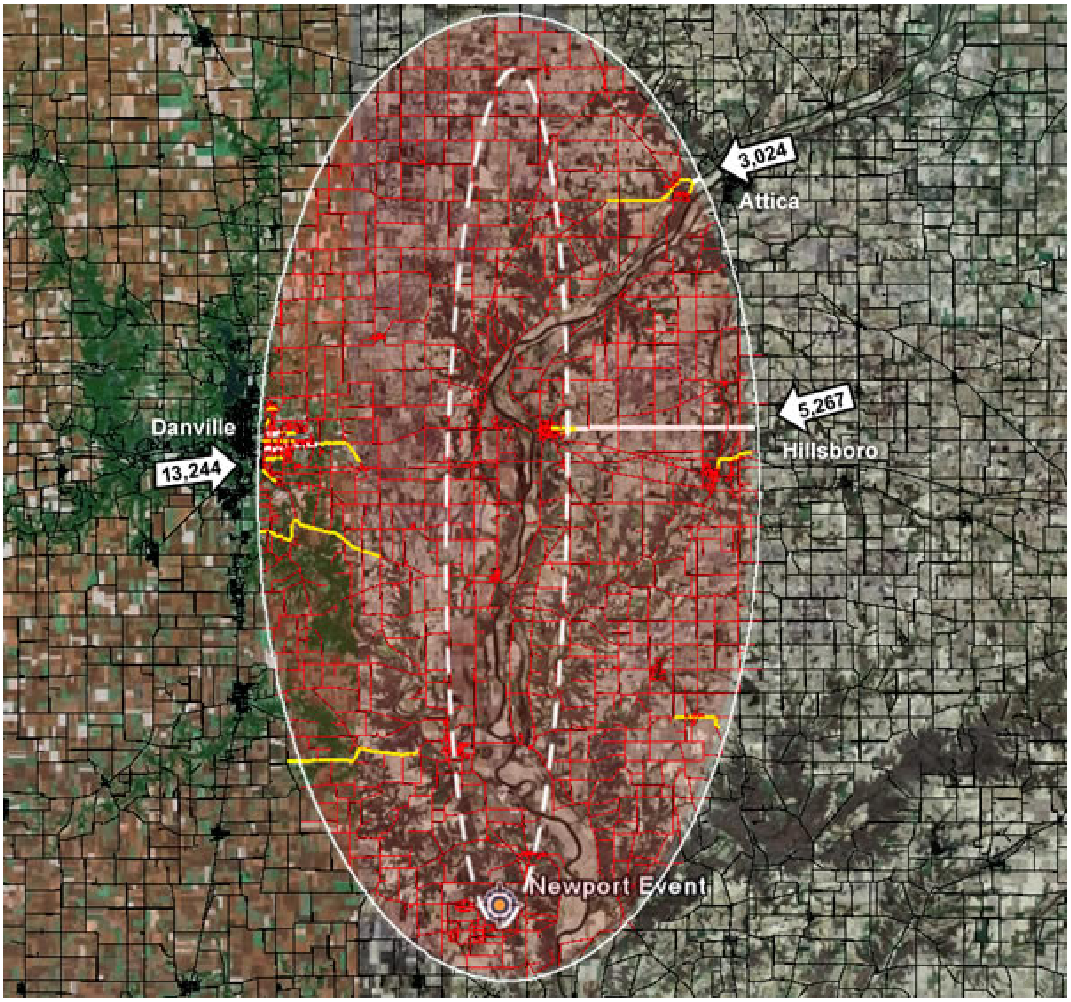

Figure 13. Newport Chemical Depot Evacuation Result (Scen. 2: S Wind)
(The key in Figure 12 also applies to this figure.) No major cities fall within the evacuation area and the dense road network helps move traffic out of the evacuation area. Traffic along the shortest-path routes reaches a maximum of 4,129 persons on Madison Road, and at least 13,244 persons evacuate into the Danville area. Table 5 lists the high-intensity and medium-intensity traffic. In addition to mapping the roads listed in Table 5, Figure 13 maps roads with medium-intensity traffic having intensity greater than 800 persons per road.

High-Intensity Traffic Roads		Medium-Intensity Traffic Roads	
Road Name	Persons	Road Name	Persons
Madison	4,129	Division	2,246
Bowman Avenue	4,003	United States Highway 41	2,246
U.S. Highway 136	3,832	Perrysville	2,118
Plum	3,832	Old Covington	2,114
River	3,024	I-74	2,103
100	2,989	Cemetery	2,012
Stone Bluff	2,878	4th	1,997
Fairchild	2,834		

Table 5. Newport Road Traffic (Scenario 2: S wind, 10 mph)

As in Scenario 1, the dense emergency-response system helps to reduce the impact to the local area from the Scenario-2 catastrophe. Results from the ERS models show that only areas north and northeast of the evacuation area experience substantial increases in ERS distances; see Figure 14.

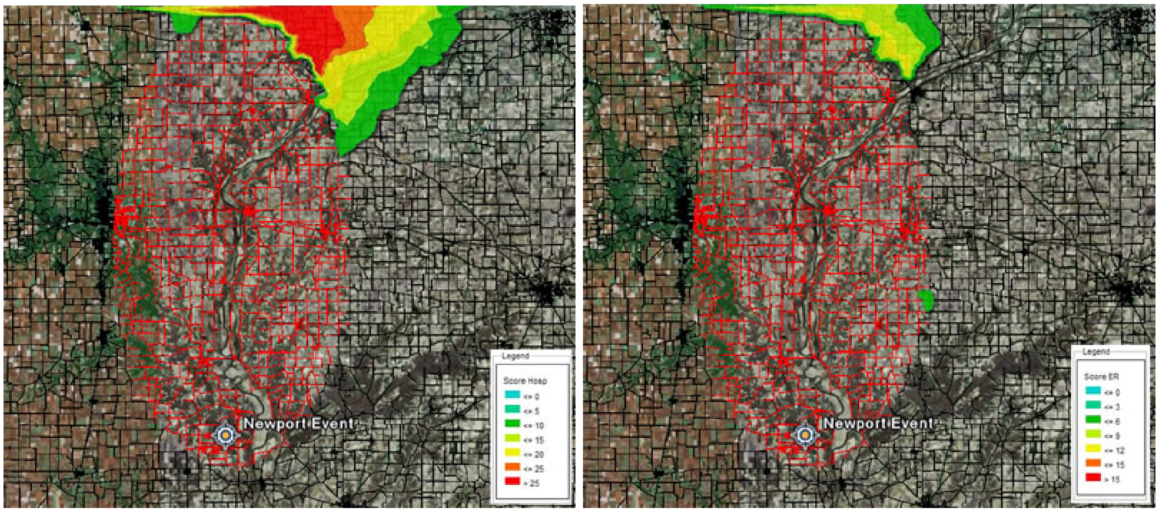

Figure 14. Newport ERS Results, Scen. 2: Hospitals (Left) and ER (Right).
Key: In MINO$_{ERS}$ figures, legend numbers represent the increased distance in miles for hospital facilities and emergency-responders (ER) for a given area. The contours result from mapping all population groups together.
In Scenario 2, a few population locations just north and northeast of the evacuation area exhibit substantial increases in both hospital and ER distances. For the hospital distances, the "distance-change scale" ranges from zero to greater than 25 miles. Population nodes in the red (dark) area would see travel distances increase over 25 miles to reach the nearest hospital. The ER distance increases range from zero to greater than 15 miles. Only a few areas north of the evacuation area see ER increases in excess of 12 miles. (The reader is warned that some vulnerabilities may be artificially induced by MINO boundaries; see the discussion in the text.)

<u>Caveat 2</u>.

ERS distances for population nodes near a boundary edge may improve if other ERS locations exist just beyond the edges of that boundary. In fact, inspection of actual ERS data north of the Newport MINO area shows additional hospital and ER locations that may negate the discussed vulnerabilities. This will be the case for all CF MINO$_{ERS}$ results along the edge of the model area.

3. Summary (Newport)

Few large cities are situated near the Newport Chemical Depot, and the Depot is surrounded by a robust road network and emergency-response system. Using two scenarios with a container VX chemical catastrophe in prevailing wind conditions, evacuees ranged from 23,000 – 40,000 persons, which are spread nearly uniform across

multiple exit routes. The traffic intensities reach a maximum of 4,100 persons on a single road, which suggests minimal traffic-congestion problems. The safe population areas outside the evacuation area see little change in response distances to both hospitals and emergency-responders. In Scenario 2, with a south wind, some population areas in the north do see increases in ERS distances. This is the only potential vulnerability highlighted by the ERS models (but see Caveat 2).

C. ANNISTON CHEMICAL ACTIVITY, ALABAMA

1. Parameters and Data Processing (Anniston)

For the Anniston Chemical Activity, the MINO area covers an area roughly 45 miles wide and 60 miles tall. The entire network includes 51,949 road segments, 6,358 population nodes encompassing 299,599 people, and 130 emergency-response locations.

NOAA historical wind data does not provide wind conditions at the Anniston location, so data from the nearest city, Birmingham, is used for the two scenarios investigated here. The Birmingham prevailing wind directions are from the north (N) for nine out of twelve months and are south (S) for the remaining three months (NOAA NCDC 1998). Wind speeds ranged from 6-9 mph. The Anniston chemical catastrophes, centered at 33.68N, 85.963W, use the Birmingham wind data and following parameters in two different scenarios; see Table 6. Figure 15 shows the two corresponding catastrophe-scenario results from HPAC.

HPAC Settings	Level	Winds	Type
Agent	VX (Nerve)	1. N (360 degrees) @ 9 mph	Prevailing
Facility Type	Weaponized VX	2. S (180 degrees) @ 8 mph	Prevailing
Construction	Bermed		
Weapon Size	500 lbs		

Table 6. Anniston Chemical Activity Scenario Parameters.

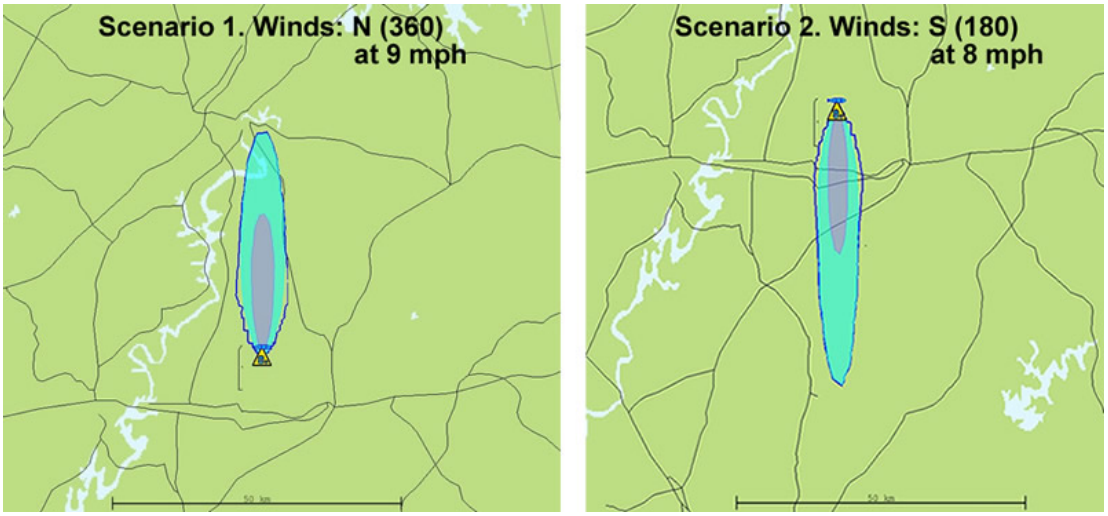

Figure 15. Anniston Chemical Activity Chemical Catastrophes
Figures show contamination areas for two different scenarios.

2. Analysis and Results (Anniston)

The first scenario (N wind, 9 mph), generates a large evacuation area in which 59,159 persons evacuate from 1,207 population nodes. Figure 16 shows the resulting $\text{MINO}_{\text{EVAC}}$ network with roads, evacuation area, and highlighted high-traffic roads.

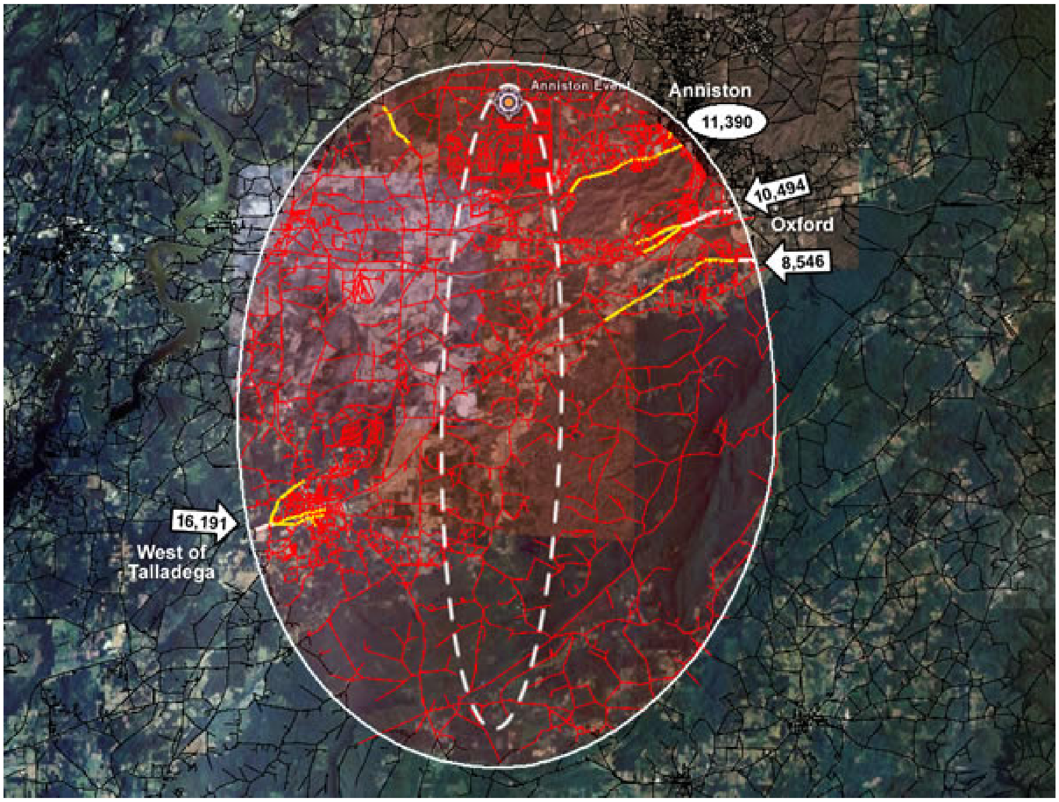

Figure 16. Anniston Chemical Activity Evacuation Result (Scen. 1: N Wind)
(The key in Figure 12 also applies to this figure.) The larger cities of Talladega and Oxford would evacuate creating a large amount of traffic in the southwest and northeast of the evacuation area, respectively. The highest-intensity evacuation route heads southwest through Talladega; it carries 14,646 persons. Table 7 lists the high-intensity traffic and medium-intensity traffic roads. In addition to mapping the roads listed in Table 7, Figure 16 maps roads with medium-intensity traffic having intensity greater than 2,000 persons per road.

High-Intensity Traffic Roads		Medium-Intensity Traffic Roads	
Road Name	Persons	Road Name	Persons
Renfroe	14,646	Fort Lashley	5,813
Mc Millan	11,381	Battle	5,543
Coleman	10,494	South	5,449
U.S. Highway 78	10,386	Alabama Highway 202	5,332
Friendship	6,141	Clydesdale	5,332
Jewell	6,141	Palmetto	5,332

Table 7. Anniston Road Traffic (Scenario 1: N Wind, 9 mph)

The ERS surrounding Anniston, with 130 locations, has good, redundant coverage for the N-wind scenario, except to the southwest of the evacuation area. Population groups there see a significant increase in ERS distances. With a smaller number of hospitals compared to emergency-responders, more population areas see an increase in hospital distances; see Figure 17. (And note Caveat 2.)

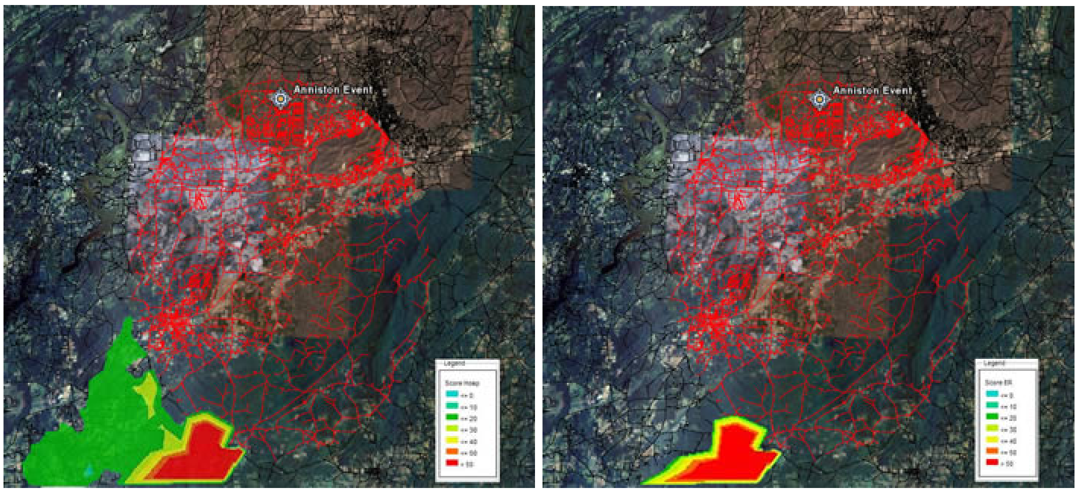

Figure 17. Anniston ERS Result, Scen. 1: Hospitals (Left) and ER (Right) (The key in Figure 14 also applies to this figure.) The hospital distances range up to 50 miles. The red (dark) area southwest of the contamination area experiences a distance increase of over 50 miles. A large green area west of that would also expect hospital distances to increase more than 20 miles. The emergency-responder distances increase up to 50 miles with a similar distribution to the hospital results, but only in the red (dark) region.

The second Anniston scenario (S wind, 8 mph), creates another large area in which 1,496 population nodes evacuate with 77,234 persons. Figure 18 shows the resulting $\text{MINO}_{\text{EVAC}}$ network with roads, evacuation area, and highlighted high-traffic roads.

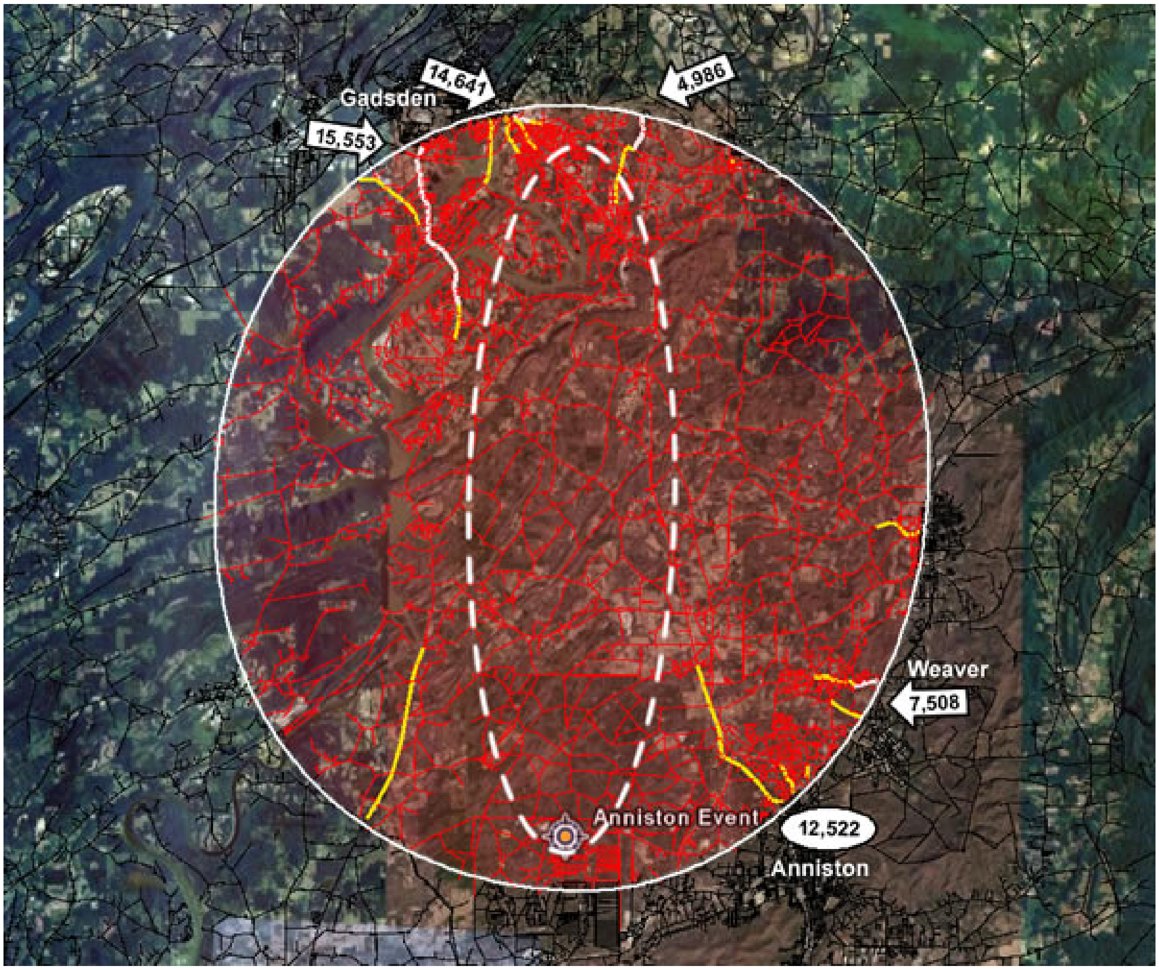

Figure 18. Anniston Chemical Activity Evacuation Result (Scen. 2: S Wind) (The key in Figure 12 also applies to this figure.) In this scenario, the primary evacuation routes lead through the city of Gadsden to the northwest and through Anniston and Weaver to the southeast. The largest evacuation routes in the northwest carry over 30,000 persons out of the area. Table 8 lists the high-intensity traffic and medium-intensity traffic roads. In addition to mapping the roads listed in Table 8, Figure 18 maps roads with medium-intensity traffic having intensity greater than 2,000 persons per road.

High-Intensity Traffic Roads		Medium-Intensity Traffic Roads	
Road Name	Persons	Road Name	Persons
Piedmont	11,019	Cole	3,913
Sutton Bridge	11,019	U.S. Highway 278	3,897
Church	8,089	Old Gadsden	3,879
Highway 77	7,961	Parker	3,844
Meighan	7,659	Mountain	3,726
Walker	4,670	Forney	3,726
Caddell	4,580	Main	3,722
Blarney	4,575	2nd	3,564
		Elmwood	3,551
		Alabama Hwy 204	3,495

Table 8. Anniston Road Traffic (Scenario 2: S Wind, 8 mph)

The $\text{MINO}_{\text{ERS1}}$ model for the second scenario indicates that areas to the north will experience large travel-distance increases to reach a hospital (but see Caveat 2), and the results from $\text{MINO}_{\text{ERS2}}$ show that the emergency-responder distances increase only slightly; see Figure 19.

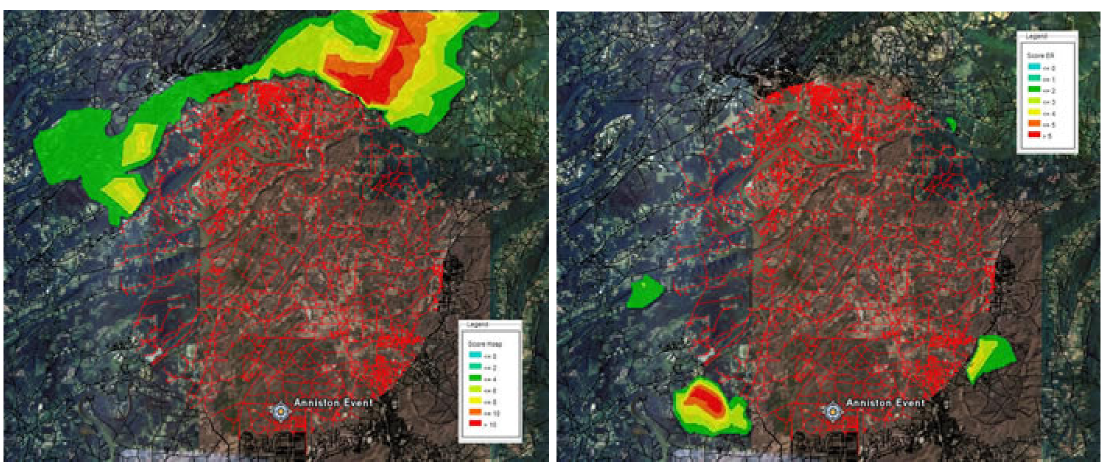

Figure 19. Anniston ERS Results, Scen. 2: for Hospitals (Left) and ER (Right) The dark red areas, in the left half of Figure 19, will experience hospital distance increases greater than 10 miles. The dense emergency-responder network shows little impact for population nodes after the catastrophe, with the greatest distance increase of only five miles for the small highlighted area straight west of the Anniston Chemical Activity.

3. Summary (Anniston)

The area surrounding the Anniston Chemical Activity is similar to the Newport area in population size, but has a sparser road network and fewer ERS locations. With a weaponized VX chemical catastrophe and prevailing wind conditions, the resulting evacuation areas require between 60,000 and 77,000 persons to evacuate. In both scenarios, the evacuating population flows out of the area through two or three main traffic corridors. In the north-wind scenario, the area west of Talladega and the areas around Anniston and Oxford see the greatest evacuation population numbers and, consequently, the greatest increase in traffic. A few main roads in these areas show traffic exceeding 10,000 persons. With a relatively robust ERS, the distances for hospitals and emergency-responders increase substantially only for a small area in the south, along the geographical boundary of MINO. (See Caveat 2, however.)

The south-wind scenario creates even more evacuating population with the area around Gadsden receiving the largest portion, over 30,000 persons. Roads in the Gadsden area, as well as the Anniston and Weaver areas, see large amounts of traffic that may over-burden the road network. Although several areas north of the evacuation area see small increase in ERS distances, the area may still require an augmentation of services given the somewhat-increased response times coupled with the large number of evacuees arriving to the area. (Again, see Caveat 2.)

D. BLUE GRASS CHEMICAL ACTIVITY, KENTUCKY

1. Parameters and Data Processing (Blue Grass)

For the Blue Grass Chemical Activity, MINO defines an area roughly 50 miles wide and over 50 miles tall. The entire network model includes 44,043 road segments, 5,028 population nodes encompassing a large population of 495,004 people, and 150 emergency-response system locations.

The NOAA historical wind data does not provide data at the Richmond, Kentucky location, so the data used for this test comes from the nearest city of Lexington, Kentucky

just 20 miles to the northwest. For Blue Grass, the single prevailing wind for Lexington was chosen for the first scenario. A south (S) wind averaging 7-11 mph is prevalent all year-round for this part of Kentucky (NOAA NCDC 1998). A second, worst-case scenario will examine a southeast (SE) wind which will directly affect the nearby city of Richmond.

The Blue Grass Chemical Activity chemical catastrophes are centered at location 37.72N, 84.215W. Table 9 depicts the parameters utilized in the two different HPAC scenario runs.

HPAC Settings	Level	Winds	Type
Agent	GB (Nerve)	1. S (180 degrees) @ 11 mph	Prevailing
Facility Type	Weaponized	2. SE (140 degrees) @ 11 mph	Worst Case
Construction	Bermed		
Weapon Size	1000 lbs		

Table 9. Blue Grass Chemical Activity Scenario Parameters.

Figure 20 shows the two catastrophe scenario results output from HPAC, with winds S and SE.

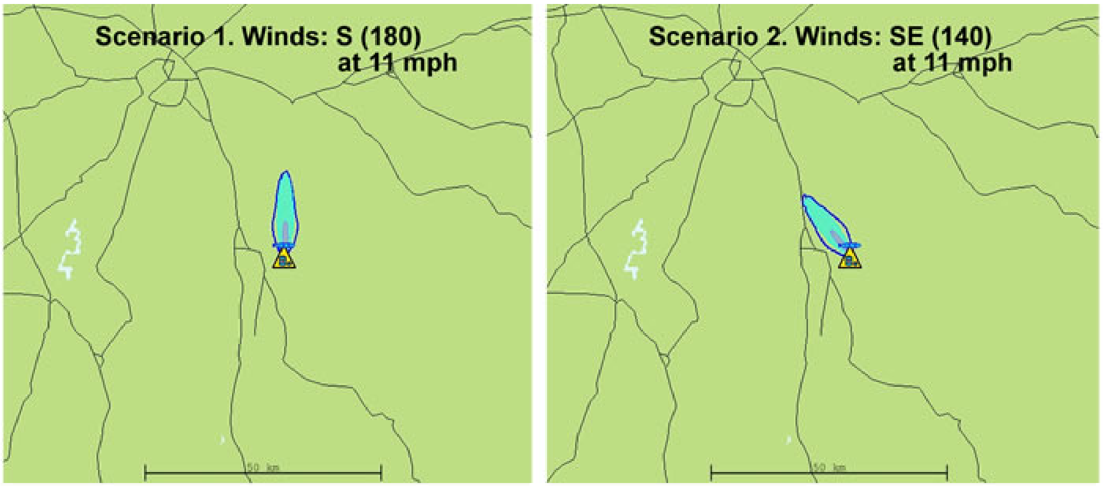

Figure 20. Blue Grass Chemical Activity Chemical Catastrophes
Figures show contamination areas for two different scenarios.

2. Analysis and Results (Blue Grass)

The first scenario (S wind at 11 mph), creates an evacuation area nearly ten miles long in which 36,434 persons evacuate from 349 population nodes. Of note, a weaponized GB scenario generates a contamination ellipse less than 50 percent the size of an analogous VX scenario. Figure 21 shows the resulting $MINO_{EVAC}$ network with roads, evacuation area, and highlighted high traffic roads.

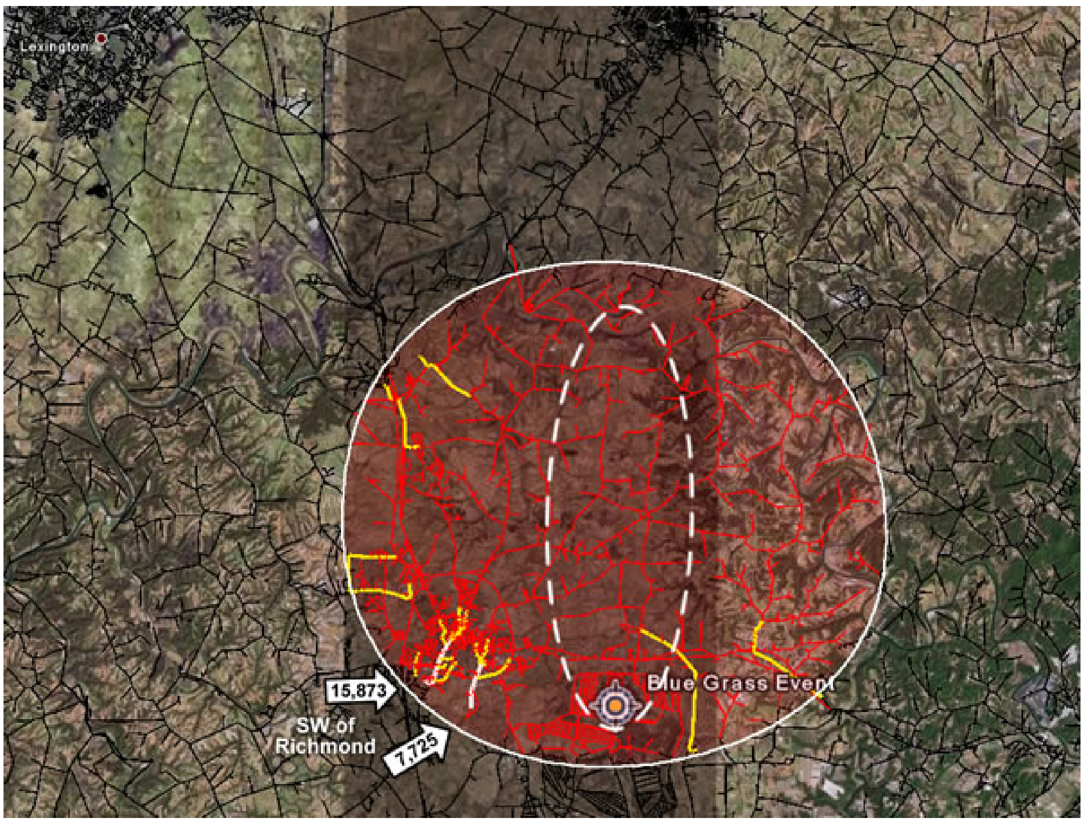

Figure 21. Blue Grass Chemical Activity Evacuation Result (Scen. 1: S Wind) (The key in Figure 12 also applies to this figure.) The largest evacuation routes head southwest from the city of Richmond with over 20,000 evacuating persons. Table 10 lists the high-intensity traffic and medium-intensity traffic roads. In addition to mapping the roads listed in Table 10, Figure 21 maps roads with medium-intensity traffic having intensity greater than 900 persons per road.

High-Intensity Traffic Roads		Medium-Intensity Traffic Roads	
Road Name	Persons	Road Name	Persons
Reynolds	12,695	Wellington	3,922
Lancaster	12,635	3rd	3,716
Elizabeth	12,635	Big Hill	2,604
Cycle	7,725	Boggs	2,604
Boggs	7,714	Steep	2,505
		Eastern	2,452

Table 10. Blue Grass Road Traffic (Scenario 1: S Wind, 11 mph)

MINO$_{ERS1}$ shows that distances to hospitals increase significantly for areas just southwest of Richmond, see Figure 22. (See Caveat 2.) In MINO$_{ERS2}$, only a few population groups see distance increases, and those increases are all less than five miles; therefore the corresponding results figure is omitted.

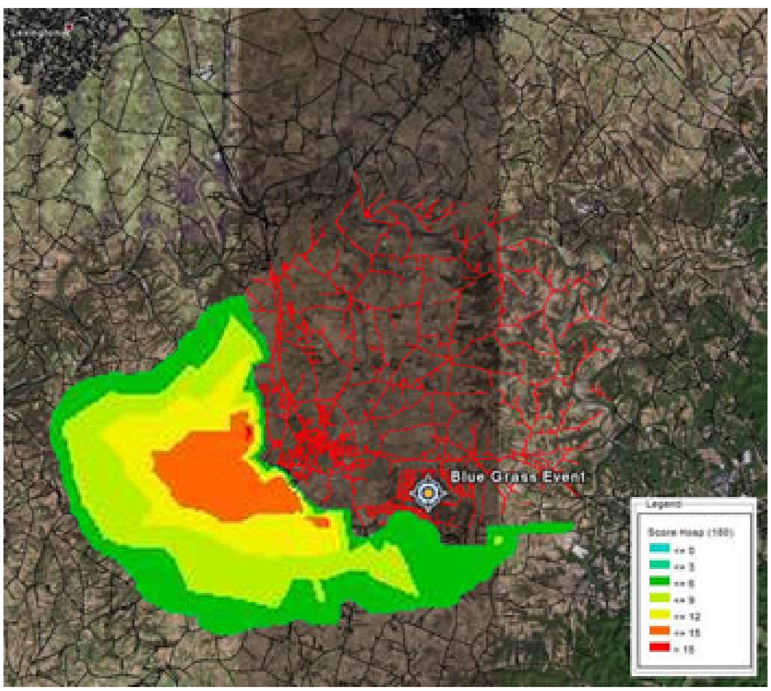

Figure 22. Blue Grass ERS Result, Scen. 1: Hospitals.
The changes in hospital distance for the areas west and south of the Blue Grass evacuation area range from 6 to over 15 miles. The center areas in orange (dark) are affected most, and would expect to see an increase of over 15 miles to the nearest hospital.

The second Blue Grass scenario (SE wind at 11 mph), creates a similar evacuation area with 366 population nodes evacuating 39,213 persons. The resulting $MINO_{EVAC}$ network with roads, evacuation area, and highlighted high traffic roads can be seen in Figure 23.

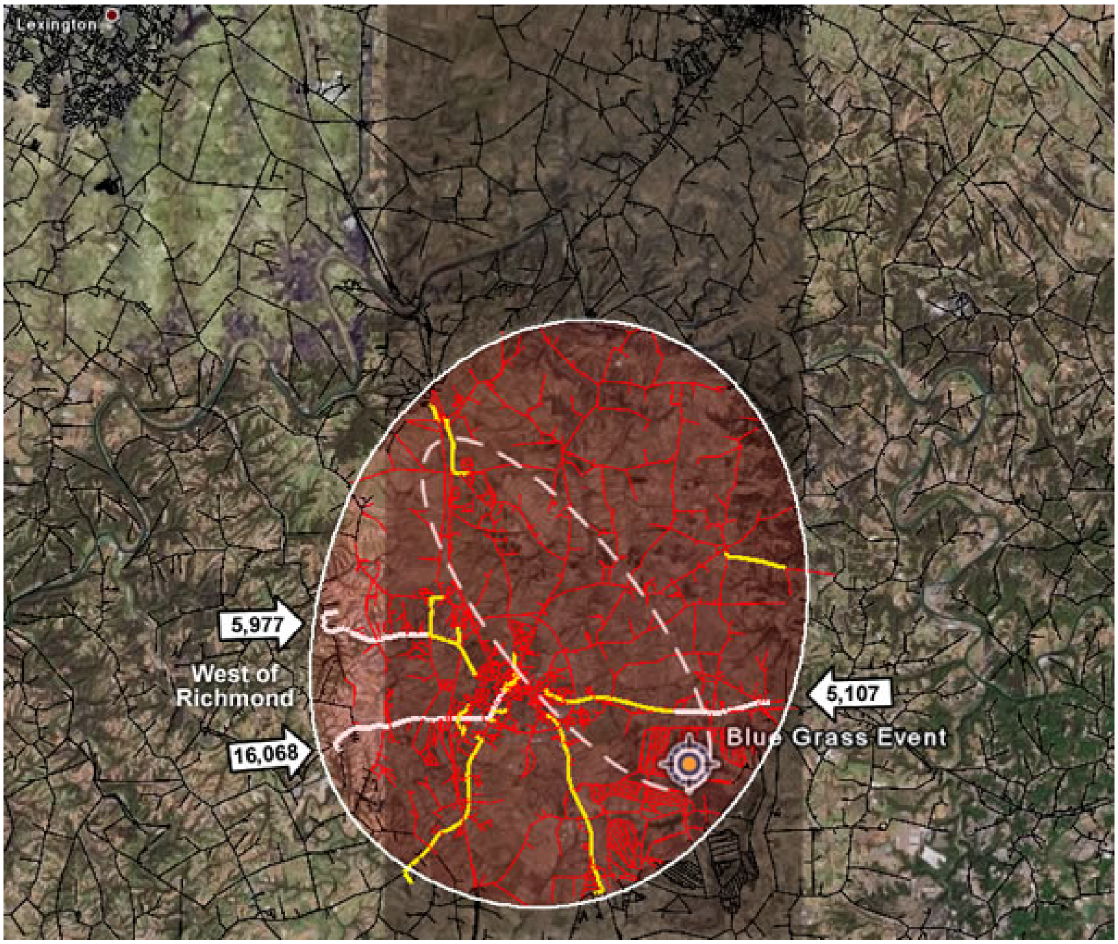

Figure 23. Blue Grass Chemical Activity Evacuation Result (Scen. 2: SE Wind) (The key in Figure 12 also applies to this figure.) Traffic flows largely to the west out of Richmond with the Redwood and Tates Creek roads carrying over 20,000 evacuating persons. Table 11 lists the high-intensity traffic and medium-intensity traffic roads. In addition to mapping the roads listed in Table 11, Figure 23 maps roads with medium-intensity traffic having intensity greater than 1,000 persons per road.

High-Intensity Traffic Roads		Medium-Intensity Traffic Roads	
Road Name	Persons	Road Name	Persons
Redwood	16,068	Wellington	3,740
Barnes Mill	16,068	McKee	3,734
Eastern	14,597	General Nelson	3,734
Lancaster	8,569	3rd	3,534
Tates Creek	5,977	Berea	3,206
Old Ky 52	4,853	Wildcat	2,287
Irvine	4,209	Park	2,253
		State Highway 52	2,246
		Kit Carson	2,208
		Big Hill	2,204

Table 11. Blue Grass Road Traffic (Scenario 2: SE Wind, 11 mph)

In Scenario 2, both the distances to hospitals and emergency-responders are affected, see Figure 24. The MINO$_{ERS1}$ Scenario 2 results nearly duplicate the results from Scenario 1, which is not all that surprising given the small change in wind direction (40 degrees). Unlike Scenario 1, MINO$_{ERS2}$ does identify areas that are impacted by the loss of emergency responders. (Caveat 2 applies to the discussion above.)

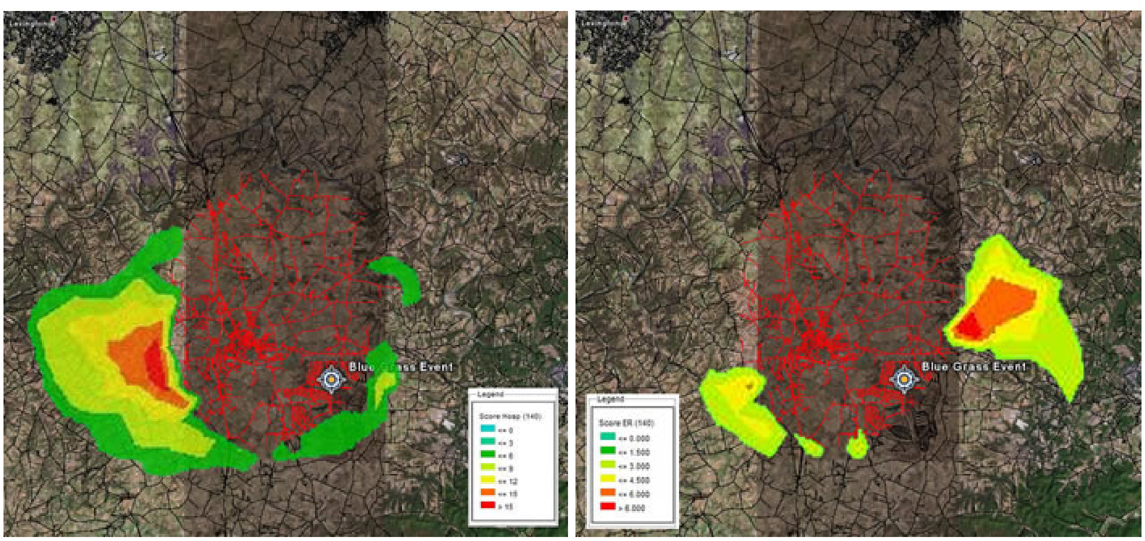

Figure 24. Blue Grass ERS Result, Scen. 2: Hospitals (Left) and ER (Right) The results and distance-change scale for hospitals is nearly identical to Scenario 1. For the changes in hospital distance, the areas in orange and red (dark) see an increase of over 15 miles. For emergency responders, the orange and red area northeast of Blue Grass shows a distance increase over five miles.

3. Summary (Blue Grass)

The Blue Grass Chemical Activity MINO includes a population of over 495,000 persons. Fortunately, the weaponized GB chemical catastrophe scenarios, using the prevailing wind condition and a worst-case wind condition, not spark mass evacuations. Fewer than 40,000 persons evacuate in each scenario. In the first scenario, with a south wind, a few roads southwest of the Richmond area see significant traffic, with over 12,000 persons. This area also becomes the primary departure point for the nearly two-thirds of the evacuating population. Additionally, with no hospital facilities available in this area southwest of Richmond, hospital distances increase considerably, (See Caveat 2.)

Similar results follow for a second, worst-case scenario as the majority of evacuating population departs west out of Richmond. Again, a few roads carry large numbers of persons, with up to 16,000 persons on the main roadway. Hospital distances increase as in the first scenario because the area west of Richmond has limited hospital facility infrastructure. (See Caveat 2.) Overall, given the likely south wind for the Blue Grass area, the road network and ERS appear vulnerable and may quickly reach capacity in the areas south and west of Richmond.

E. PUEBLO CHEMICAL DEPOT, COLORADO

1. Parameters and Data Processing (Pueblo)

For the Pueblo Chemical Depot, MINO defines an area roughly 60 miles wide and 50 miles tall. The combined network includes 20,372 road segments, 3,015 population nodes, and 31 emergency-response system locations. The model population includes 145,799 people.

The NOAA historical wind data establishes two prevailing wind conditions for Pueblo. For two months, January and February, the prevailing wind is from the west (W) from 7-8 mph, and for the other ten months, the prevailing winds are from the east-south-east (ESE) at 7-11 mph (NOAA NCDC 1998).

The Pueblo chemical catastrophes are centered at location 38.345N, 104.32W. Initial results from $MINO_{EVAC}$ and $MINO_{ERS}$ show that the two prevailing wind directions have little impact on the local infrastructure so a third more devastating wind direction of east-north-east (ENE) is added for analysis. Table 12 displays the parameters utilized in the three different HPAC scenarios run for the Pueblo area.

HPAC Settings	Level	Winds	Type
Agent	HD (Mustard)	1. ESE (115 degrees) @ 11 mph	Prevailing
Facility Type	Weaponized	2. W (270 degrees) @ 9 mph	Prevailing
Construction	Light Steel	3. ENE (060 degrees) @ 10 mph	Worst Case
Weapon Size	500 lbs		

Table 12. Pueblo Chemical Depot Scenario Parameters.

A few of the levels for Pueblo HPAC settings are altered to create worse-than-likely scenarios for analysis. One setting with a large impact to contamination area is the type of bunker or storage-facility construction. Most of the chemical weapons stored at the Pueblo Chemical Depot are housed in bermed, concrete bunkers. With mustard agent and bermed bunkers chosen in HPAC, the resulting contamination area would remain within the confines of the military installation. While this is a comforting result, these parameters were relaxed to test the Pueblo MINO. A more severe case assuming only steel construction housing the chemical weapons is utilized for the scenario calculations. Although less likely, this situation could occur during transport of a chemical weapon or in a destruction facility.

Figure 25 shows the three results from HPAC, with winds ESE, W, and ENE from left to right respectively.

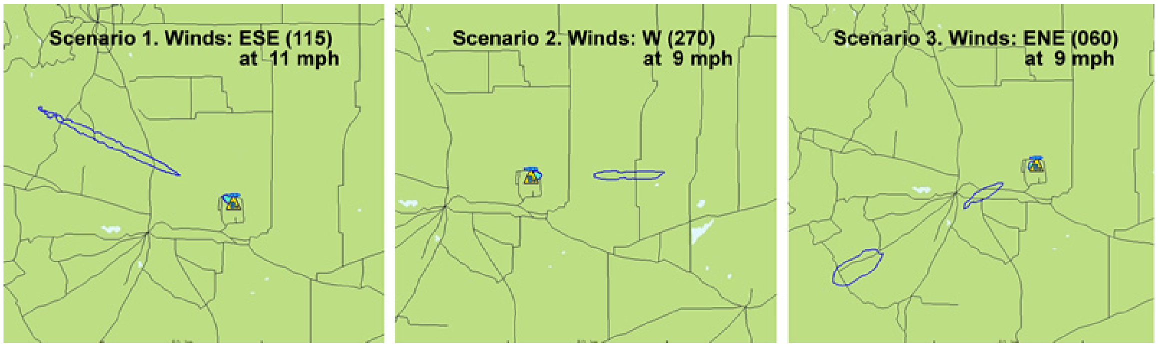

Figure 25. Pueblo Chemical Depot Chemical Catastrophes
Figures show contamination areas for three different scenarios.

2. Analysis and Results (Pueblo)

As alluded to earlier, the first two wind directions, ESE and W prevailing winds, do not produce significant effects on the local infrastructure. Even with the expanded evacuation area, the number of evacuees remain below 200 persons and there is virtually no impact to the emergency-response system. Therefore, for prevailing wind directions and speeds, a major weaponized mustard-agent catastrophe starting inside a light steel building, has little impact to public safety, in general. To test vulnerabilities in the area, a third scenario with a more problematic wind direction is created.

In Scenario 3 (ENE wind at 10 mph), 2,289 locations with 123,752 people evacuate. Figure 26 shows the resulting $MINO_{EVAC}$ network, with evacuation area and major-traffic roads.

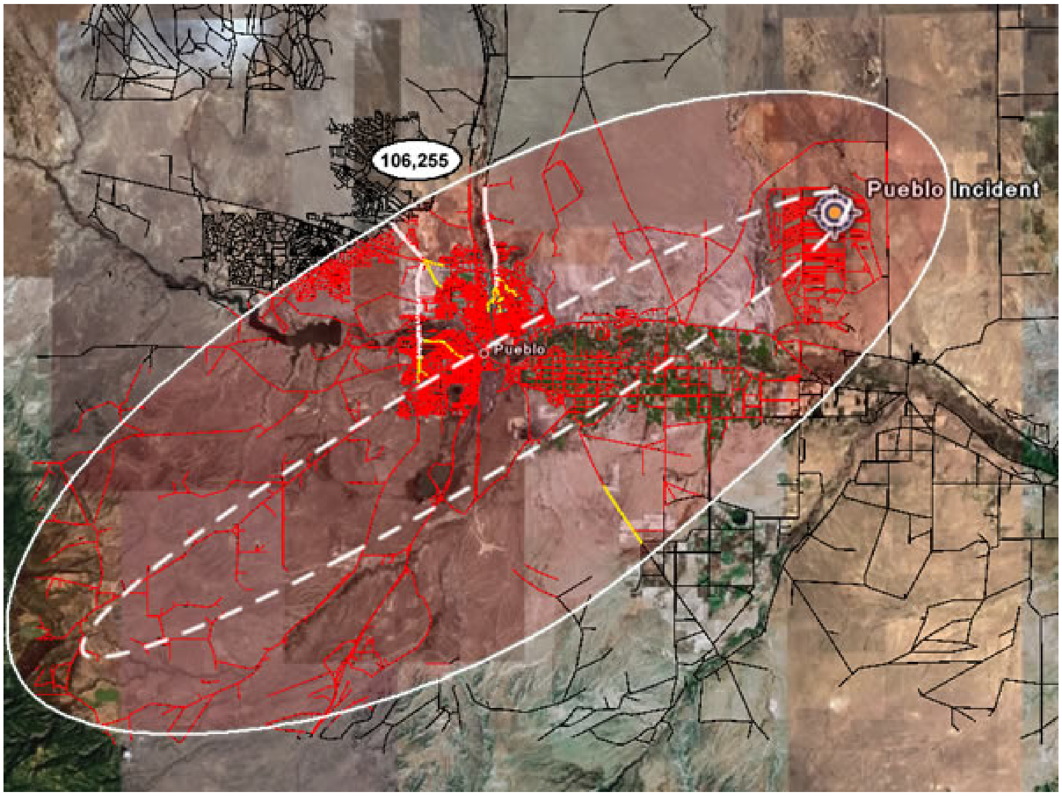

Figure 26. Pueblo Chemical Depot Evacuation Result (Scen. 3: ENE Wind) (The key in Figure 12 also applies to this figure.) The population in this scenario will likely pool north of the city or continue further north out of the area. The areas north of Pueblo see an increase of over 106,000 persons, or over 85 percent of those evacuating. The remainder of the evacuees flow out to the southeast and east of the evacuation area. Table 13 lists the roads with the largest traffic intensities.

High-Intensity Traffic Roads		Medium-Intensity Traffic Roads	
Road Name	Persons	Road Name	Persons
Boyero	64,098	Collins	13,546
Wildhorse	64,002	Wooden	11,311
Pueblo	57,174	Adams	11,262
Overton	42,157	Veta	10,814
Jerry Murphy	40,195	Princeton	9,663
Goodnight	17,419	29th	8,245

Table 13. Pueblo Road Traffic (Scenario 3: ENE Wind, 10 mph)

$MINO_{ERS}$ for Scenario 3 shows that all of the hospital facilities in the study area fall within the evacuation area and become unusable. In this worst case, the facilities needed

to treat any casualties (or unrelated injuries and disease) must lie outside the MINO area. However, the Pueblo area contains more emergency-responder locations and some lie outside the evacuation area, so it does make sense to analyze changes in ER distances with $MINO_{ERS2}$; Figure 27 displays those results.

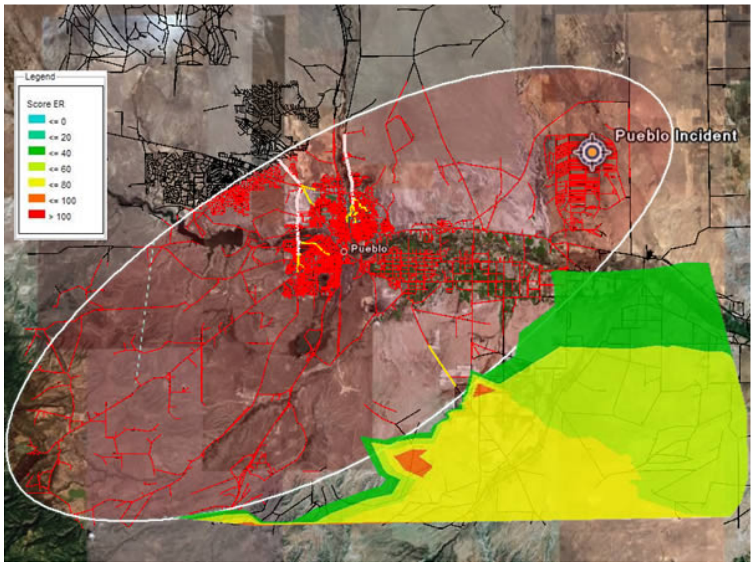

Figure 27. Pueblo ERS Result, Scen. 3: ER
For areas southeast of the evacuation area, emergency-responder distances increase significantly, with a few areas in the orange (darker) contours increasing up to 100 miles. All areas southeast of the contamination area see emergency-responder distance increases of over 60 miles, and should expect response times to increase accordingly (See Caveat 2.)

3. Summary (Pueblo)

The area surrounding the Pueblo Chemical Depot has a sparse road network, a relatively small population, and few emergency-response locations. Fortunately, the chemical agent stored in the Depot, HD mustard, is the least dangerous of those studied here, and is unlikely to produce a true chemical catastrophe. To test the Pueblo MINO, HPAC parameters must be relaxed to create a scenario in which chemical agents actually disperse beyond the borders of the military installation. With the two prevailing wind conditions, given a weaponized mustard agent chemical catastrophe, the expanded evacuation areas contain fewer than 200 persons and have virtually no impact to the ERS.

Overall, the results show no significant vulnerabilities for standard conditions in the Pueblo area. However, to test MINO and identify potential vulnerabilities, a worst-case wind direction is chosen next with an ENE wind, a direction that directly affects the city of Pueblo.

The entire city of Pueblo lies within the evacuation area, and so a large volume of traffic evacuates the area to the north towards Colorado Springs. Over 106,000 persons, about 85 percent of all the evacuees, travel along these roads. The main roads and areas just north of Pueblo would be impacted significantly with the added evacuation population. Additionally, all the hospital facilities in the study area fall inside the evacuation area and are deemed unusable. Hospital facilities outside the model area would be required, or mobile facilities could be brought into the region. While the areas north of Pueblo do not see major increases to the emergency-responder distances, the areas east of Pueblo show significant distance increases because only a few emergency-responder locations remain. The city of Pueblo, its infrastructure and population, appears to be highly vulnerable to a worst-case chemical catastrophe. (However, see Caveat 2 and recall that the scenario assumptions here are extreme.)

F. DESERET CHEMICAL DEPOT, UTAH

1. Parameters and Data Processing (Deseret)

For the Deseret Chemical Depot, MINO defines an area roughly 40 miles wide and 40 miles tall. With the large metropolis of Salt Lake City within this area, MINO must be scaled back in an attempt to stay within the limitations of the software. (As stated earlier, a different implementation could accommodate this much larger road network and population.) The minimum population node size is increased to 40 persons to reduce the number of population nodes. To increase space for road arcs, population nodes and ERS nodes are connected to the road network using only one arc, rather than the standard two. The reduced network includes 52,499 road segments, 8,142 population nodes, and 231 emergency-response system locations. The model population includes 954,607 people.

NOAA historical wind data establish two prevailing wind conditions for Salt Lake City, which lies about 25 miles to the northeast of CF. For two thirds of the year, the prevailing winds are out of the south-southeast (SSE) at 8-10 mph, and the remainder of the year the wind is out of the southeast (SE) at the same speeds (NOAA NCDC 1998). With the prevailing winds from nearly the same direction, which also coincides with a worst-case Salt Lake City event, the analysis of only one scenario is attempted here.

The Deseret chemical catastrophe is centered at location 40.308N, 112.358W. Table 14 depicts the parameters utilized in the Deseret Chemical Depot HPAC scenario.

HPAC Settings	Level	Winds	Type
Agent	VX (Nerve)	1. SE (215 degrees) @ 10 mph	Prevailing
Facility Type	Storage		
Construction	Bermed		
Weapon Size	750 lbs		

Table 14. Deseret Chemical Depot Scenario Parameters.

2. Analysis and Results (Deseret)

Given the large contamination area created by the HPAC scenario, and given the high density of population and roads in the Salt Lake City area, G^{MINO} for this area is simply too large to handle within the Excel format and MINO. Consequently, no summary or further analysis is provided in this thesis for the Deseret Chemical Depot. This large, population-dense area could be addressed in future work.

G. UMATILLA CHEMICAL DEPOT, OREGON

1. Parameters and Data Processing (Umatilla)

For the Umatilla Chemical Depot, MINO defines an area roughly 75 miles wide and 75 miles tall. The complete network includes 43,700 road segments, 5,476 population nodes encompassing 290,589 people, and 135 emergency-response system locations.

NOAA historical wind data establishes two prevailing wind conditions for Pendleton, Oregon, a location 30 miles to the east of the Umatilla area. For two thirds of the year, the prevailing wind is from the west (W) at 7-9 mph, and is from the SSE in the same speed range for the remainder of the year (NOAA NCDC 1998).

The Umatilla chemical catastrophes are centered at location 45.85N, 119.425W. Table 15 displays parameters used in HPAC to generate the two scenarios for this Depot. One prevailing-wind-direction scenario is selected along with a worst-case scenario which impacts the larger city of Kennewick, Washington, to the northeast of the CF.

HPAC Settings	Level	Winds	Type
Agent	GB (Nerve)	1. W (270 degrees) @ 9 mph	Prevailing
Facility Type	Storage Containers	2. SSW (205 degrees) @ 9 mph	Worst Case
Construction	Bermed		
Weapon Size	750 lbs		

Table 15. Umatilla Chemical Depot Scenario Parameters.

Figure 28 shows the two results from HPAC, with winds W and SSW on the left and right respectively.

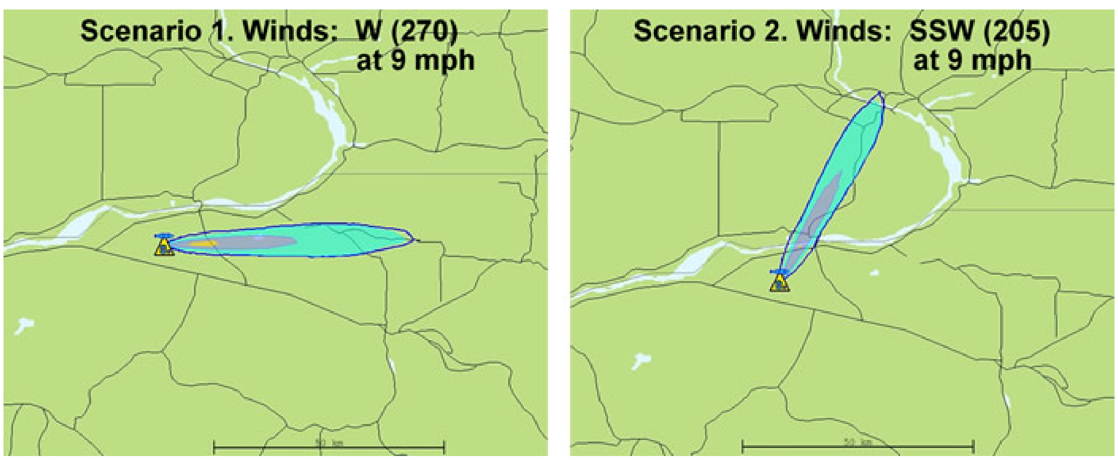

Figure 28. Umatilla Chemical Depot Chemical Catastrophes
Figures show contamination areas for three different scenarios.

2. Analysis and Results (Umatilla)

Scenario 1 (W wind at 9 mph), creates an evacuation area stretching nearly 40 miles long in which 30,921 persons from 658 population nodes require evacuation. The resulting $MINO_{EVAC}$ network with roads, evacuation area, and highlighted high-traffic roads can be seen in Figure 29.

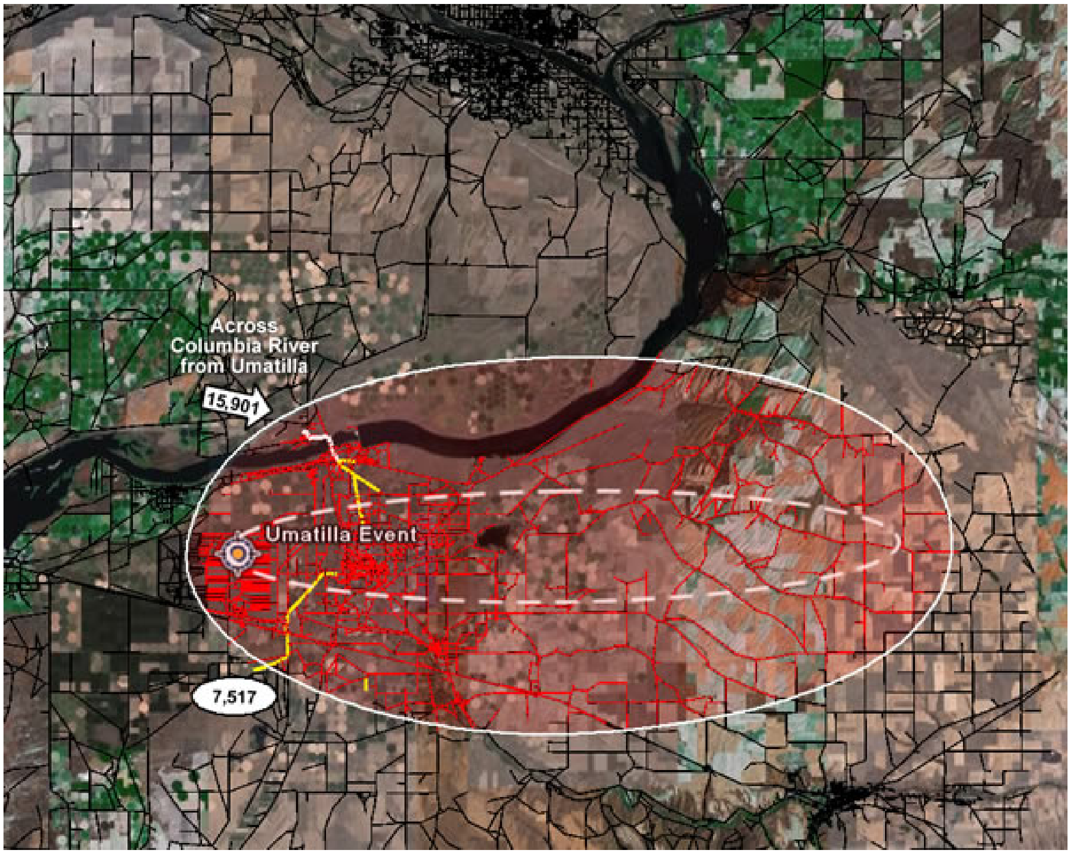

Figure 29. Umatilla Chemical Depot Evacuation Result (Scen. 1: W Wind) (The key in Figure 12 also applies to this figure.) The most heavily used evacuation routes head north across the Interstate 82 bridge spanning the Columbia River. Table 16 lists the high-intensity traffic and medium-intensity traffic roads. In addition to mapping the roads listed in Table 16, Figure 29 maps roads with medium-intensity traffic having intensity greater than 3,000 persons per road.

High-Intensity Traffic Roads		Medium-Intensity Traffic Roads	
Road Name	Persons	Road Name	Persons
I-82	15,774	Jones Scott	8,122
Plymouth	15,774	Umatilla-Stanfield	8,083
Brownell	15,713	Madison Sayler	7,465
6th	11,663	Colonal Jordan	7,465
		Westland	7,035
		Bridge	6,655

Table 16. Umatilla Road Traffic (Scenario 1: W Wind, 9 mph)

Although there are 135 ERS locations in the Umatilla $MINO_{ERS}$, the lack of roads crossing the Columbia River and contamination of larger cities can greatly impact the ERS; see Figure 30.

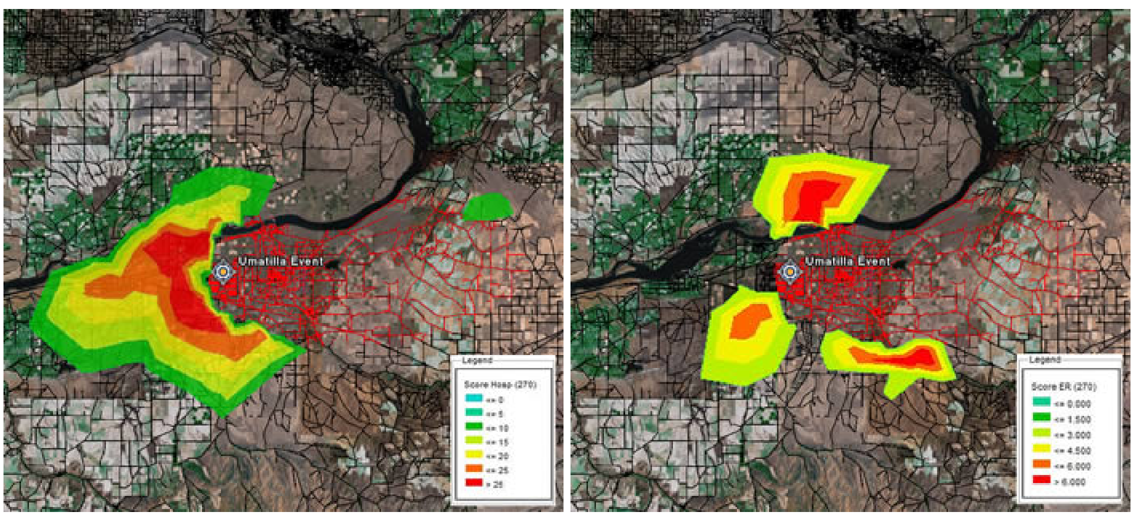

Figure 30. Umatilla ERS Result, Scen. 1: Hospitals (Left), ER (Right). In this first scenario, hospital distances increase in excess of 25 miles for areas in red and orange (dark center) west of the chemical catastrophe. An even larger area of population, in yellow and greens (outer edges), will see distance increases greater than 15 miles to the nearest hospital. The emergency-responders are less impacted with the greatest distance increase just over six miles. Although there are several large areas in the ER figure, the increase in distances for emergency-responders is not as significant as seen with hospitals.

The second scenario (SSW wind at 9 mph), generates another large contamination area stretching into the town of Kennewick, Washington. A much larger population falls within the evacuation area where 1,995 population nodes encompassing 127,935 persons must evacuate. Figure 31 displays the resulting $MINO_{EVAC}$ network with roads, evacuation area, and highlighted high-traffic roads.

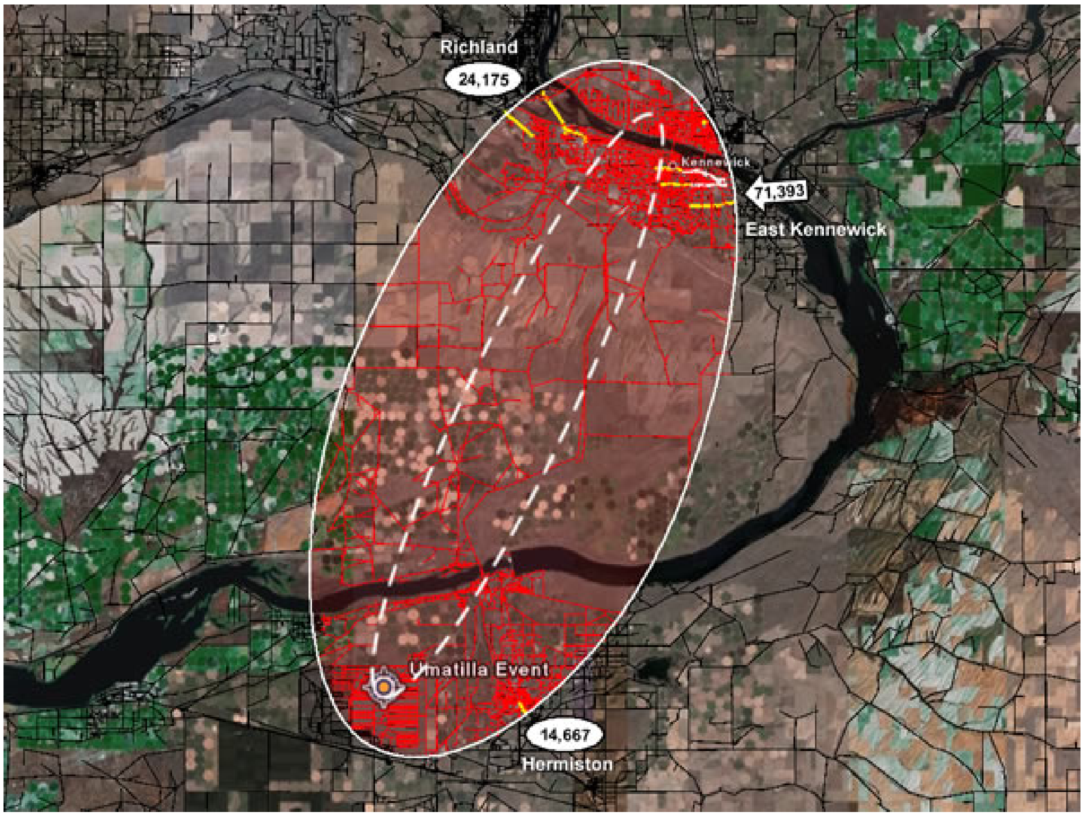

Figure 31. Umatilla Chemical Depot Evacuation Result (Scen. 2: SSW Wind) (The key in Figure 12 also applies to this figure.) The most heavily used evacuation routes are depicted, exiting the city of Kennewick to the east, and west to Richland. As the figure shows, nearly 100,000 persons must evacuate the Kennewick area creating a significant traffic problem. Table 17 lists the high-intensity traffic and medium-intensity traffic roads. In addition to mapping the roads listed in Table 17, Figure 31 maps roads with medium-intensity traffic having intensity greater than 5,000 persons per road.

High-Intensity Traffic Roads		Medium-Intensity Traffic Roads	
Road Name	Persons	Road Name	Persons
10^{th}	20,474	George Washington	13,155
Chemical	20,444	State Highway 240	13,155
19th	20,444	Carmichael	11,628
Yew	20,444	Kennewick	11,340
7th	18,123	Highway 395	10,233
3rd	17,731	25th	7,363
Oak	17,731	27th	7,253
Gum	16,804	Columbia Center	5,706
1st	16,783	Steptoe	5,639
Vineyard	16,362	Orchard	5,575

Table 17. Umatilla Road Traffic (Scenario 2: SSW Wind, 9 mph)

Since the model only moves evacuees to the edge of the evacuation area, we would presume evacuees traveling east from Kennewick would have adequate bridge capacity to travel across the Columbia River. According to the $MINO_{EVAC}$ road data, those specific evacuees would be stranded, as no safe bridges exist across the Columbia outside the evacuation area. Therefore, evacuees would more likely travel longer distances through the evacuation area across the bridges in Kennewick or to the west. In other words, evacuees would follow longer paths that would tend to increase their risk of exposure to the chemical agent.

As noted earlier, a portion of population east of the contaminated area will be isolated, without safe travel routes. Hospital distances are impacted significantly in this scenario, as highlighted by $MINO_{ERS1}$; see Figure 32. Some emergency-responders are located within the isolated area as well as in other areas, and this means that emergency-responder distances are barely affected in this scenario; the corresponding ER figure is therefore omitted.

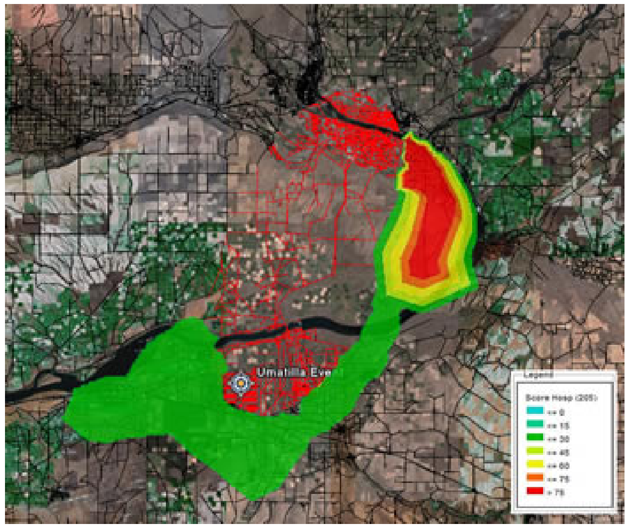

Figure 32. Umatilla ERS Result, Scenario 2: Hospitals
Of the 11 ERS hospital locations, none of the hospitals fall within this red (dark) isolated area bounded by the evacuation area and the Columbia River. Therefore, the isolated population cannot reach a hospital using the road network. Alternate means via the river or air would be required to move further from the evacuation area without reentering and risking exposure. Another large number of population groups would see hospital distances increase over 30 miles, depicted by the green areas southwest of the Umatilla Chemical Depot.

3. Summary (Umatilla)

The Umatilla Chemical Depot area studied roughly 5,600 square miles of Oregon and Washington, the largest of the MINO areas. With a GB storage facility chemical catastrophe, two vastly different scenarios result, depending solely on differing wind directions. The prevailing westerly wind generates a large evacuation area, but only requires evacuation of 31,000 persons. The majority of those persons cross the Columbia River in their shortest path, highlighting the importance of the Interstate 82 bridge. With the contamination of the ERS locations east of Umatilla, population groups west of the evacuation area would see a large distance increase, greater than 15-30 miles, to the nearest hospital. (See Caveat 2.)

The worst-case wind scenario creates a large evacuation area stretching into the town of Kennewick, Washington. In this case, over 127,000 persons require evacuation. This evacuation creates high traffic volumes on numerous roadways, especially in the

Kennewick area, but also in the Richland and Hermiston areas. These areas could expect to see large increases in population with the possibility of large numbers of exposed persons. Results from $MINO_{EVAC}$ isolate a large portion of the evacuating population between the evacuation area and the Columbia River. This fact may be viewed as a model limitation, as a logical evacuation plan would require evacuees to follow longer routes within the evacuation area to reach safe areas that are not isolated. Nevertheless, for any isolated population group, an alternate transportation system to transit from the isolated area may be necessary, e.g., watercraft on the river. The hospital distances increase for several areas surrounding the evacuation area. With several bridges unusable, this situation would also require alternate transportation solutions.

V. CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY

This thesis has created a model called MINO (multi-infrastructure network operations model) to identify vulnerabilities in select infrastructure systems to the release of a chemical-weapons agent. MINO is applied to the road networks, emergency-response systems, and public-health systems in the areas surrounding each of five U.S. Chemical Warfare Stockpiles and Facilities (CFs). Each CF is subjected to several hypothetical "chemical-catastrophe scenarios," and variants of MINO (1) identify roads that are likely to become congested during the evacuation that must take place, (2) identify areas in the "safe zone" (outside the evacuation zone) that will need to accommodate large numbers of evacuees (3) identify safe-zone areas in which emergency-response times will increase, and (4) identify safe-zone areas in which the population will experience a significant increase in the time required to reach a hospital.

MINO first creates a generic network model that integrates representations of the local road network, population blocks, emergency-response services and public-health facilities. Chemical-catastrophe scenarios are generated by specifying a variety of parameters (e.g., wind speed, wind direction, chemical type) for the Hazard Prediction and Assessment Capability software (HPAC) currently in use by the Defense Threat Reduction Agency (DTRA). The output is a "contamination area," which is expanded with a buffer zone to define an "evacuation area." The local population must leave the evacuation area immediately, after which all roads in that area are declared unusable. Variants of the MINO network and shortest-path techniques are then used to address items (1)-(4) listed above.

The models are written in Microsoft Excel's Visual Basic for Applications (VBA), because Excel is widely accessible and used in the Department of Defense. Google Earth software helps visualize MINO and interpret MINO results.

Results from MINO highlight vulnerabilities in the road and emergency-response system (ERS) infrastructures. This should inform emergency planners as to where infrastructure deficiencies may exist and help guide improvements.

B. CONCLUSIONS AND KEY INSIGHTS

As a caveat, the reader should note that only a few hypothetical scenarios have been analyzed for each location, and these scenarios represent only a small fraction those possible. Therefore, the results from this thesis should not be considered definitive. Furthermore, results for a single CF can vary widely depending on scenario parameters. For instance, the two scenarios investigated for the Umatilla Chemical Depot in Oregon show a difference of 100,000 in the number of evacuees (starting from a total population of 290,589).

The algorithms used in MINO run quickly. With a well-developed MINO network model, a range of scenarios could be analyzed, vulnerabilities identified and those results cataloged as an on-the-shelf reference for contingency planners and emergency responders.

The MINO evacuation model can identify main road corridors used in an evacuation, and safe areas in which evacuees may congregate. This information can be used to help design better evacuation routes, give emergency responders an understanding of where traffic intensities may affect their response, and will also assist in implementing traffic-control measures. The MINO ERS model helps emergency responders and planners identify areas that may require special attention, such as assistance from outside sources.

C. FOLLOW-ON WORK

The development of MINO introduces an example of multi-infrastructure networks and systems analysis. From the macro perspective, the next step should consider integrating other infrastructure systems into the MINO model. Other infrastructure systems, such as water systems or agriculture, may have similarities which

would lend to reuse of the existing contamination logic and evacuation model (or modest modifications, thereof). Other infrastructure systems, e.g., a local electric power grid, may require substantially different models.

Several aspects of the current MINO models should be developed further. First, adding weights to roads based on road capacity would create more realistic evacuation routes as evacuees are more likely to use higher-capacity roads and highways rather than low-capacity side streets. A similar modification could address casualty capacities for the ERS, e.g., the size of hospital facilities and load capacity for emergency responders.

Second, software changes are needed to handle larger network models, and thus larger geographical regions. With the current implementation in Excel 2003, the maximum number of spreadsheet rows limits the network size, which is a function of the number of roads, population nodes, etc. For instance, the current MINO implementation cannot analyze the region surrounding the Deseret Chemical Depot near Salt Lake City, because of the dense road network and large population.

Third, a few steps in the modeling-and-analysis process require manual intervention from the user, and these should be automated. For instance, the approximation of the contamination area by an ellipse requires data imports and manual point selection. Further study should verify the validity of the elliptical contamination-area approximation. Integrating several manual steps and consolidating other disconnected steps into a single function could further simplify model processing and improve efficiency. For example, the following manual steps could be fully automated in a single process: the data for the HPAC-generated contamination area is manually transferred into Excel; the user then applies that data, in a partially manual process to generate the evacuation ellipse; and then a separate application makes structural changes to the MINO network to reflect the imposition of the evacuation area.

Fourth, with improved, automated data processing, a smart design of experiment could investigate a large range of values for wind speed, wind direction and other parameters. Generating a wider range of scenarios would help identify vulnerabilities

that are most likely to be problematic. Ultimately, the study of multi-infrastructure problems with catastrophe scenarios presents a nearly endless list of topics for future exploration.

APPENDIX A: HPAC

The following selection, provides a brief introduction to the HPAC software used in this these, was taken from the HPAC 4.04 Users Manual (DTRA 2004).

Hazard Prediction and Assessment Capability (HPAC) is a counter proliferation, counterforce tool that predicts the effects of hazardous material releases into the atmosphere and its [sic] collateral effects on civilian and military populations. HPAC assists warfighters in destroying targets containing weapons of mass destruction (WMD) and responding to hazardous agent releases. It employs integrated source terms, high-resolution weather forecasts and particulate transport algorithms to rapidly model hazard areas and human collateral effects. HPAC estimates the NBC hazards associated with releases from either facilities or weapons.

HPAC predicts NBC hazards from incidents such as the following:

- Nuclear Facility Accidents (Chernobyl, Ukraine)
- Nuclear Weapon Explosions (Hiroshima, Japan)
- Nuclear Weapon Incident/Accident, “Broken Arrow” (Palomares, Spain)
- Radiological Weapon Incident
- Chemical Facility Damage (Bhopal, India)
- Biological Facility Damage (Sverdlovsk, Russia)
- Chemical Weapons (Kamasiyha, Iraq)
- Biological Weapons (Yokosuka, Japan (alleged use by Aum Shin Rikyo))

HPAC was designed to be used by two types of users, operational and analytical:

- Operational users include pilots, soldiers, and commanders – in other words, field users responding to actual or expected events.
- Analytical users (analysts) generally are involved in research and development. HPAC generally includes default values for user inputs in order to simplify complex input for operational users. Analytical users may change these default inputs based on their subject matter expertise.

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APPENDIX B: CREATING THE MINO

A. BACKGROUND

The following Appendix expands on Chapter III, Section A, constructing the multi-infrastructure network operations model (MINO) for a given U.S. Chemical Warfare Stockpile and Facility (CF), represented by the undirected network graph G^{MINO}. The required critical-infrastructure data is extracted from various datasets and then merged, using a common reference system: latitude and longitude (lat/long) coordinates. The construction process first defines the road-network infrastructure and then integrates the emergency-response system (ERS) infrastructure, which includes the hospitals and first responders. Population must also be represented and connected to the road network.

The goal is to build a connected, undirected road, population, and emergency-response system network of nodes and arcs in Microsoft Excel using data-processing routines written in Visual Basic for Applications (VBA). All initial data files are specified in a shapefile (.shp) format (ESRI 1998). While a shapefile can be read by ESRI's ArcMap program, it does not easily convert into a traditional network dataset. Several different transformations are required to convert the shapefile data files into a useful form (University of Texas 2004).

B. ROAD NETWORK DEVELOPMENT

Road and population data are taken from the 2000 Census TIGER database (Topologically Integrated Geographic Encoding and Referencing database) available to the public through the ESRI GIS and Mapping Software Web site (ESRI 2007). The TIGER database is downloadable by county and data type, e.g. "Census Blocks 2000" and "Line Features – Roads". After downloading county road data for a given CF area from the TIGER database, the county sets are merged into a single shapefile for further processing using GeoMerge (VDS Technologies 2007). The software tool GeoMerge, a free utility available on the Internet, easily and quickly combines the county shapefiles into one large dataset. The road dataset is then filtered by lat/long in ArcMap using the

Selection Features tool to shrink the working file and ensure a maximum of 65,535 road segments, an Excel 2003 software limitation (Walkenbach 2004). This segment limit is imposed by the road-processing algorithm. This limitation could be overcome with a different implementation (using multiple spreadsheets and combining the data using VBA) or Excel 2007. With the newly filtered area in ArcMap, the selected layer is exported as a new road shapefile.

The road data shapefiles contain data based on shapes. To convert the shapefiles into a set of line segments a data transformation is necessary. The FWTools toolset first converts the road shapefile into a more usable MapInfo Interchange Format (.mif) (Warmerdam 2007). The MapInfo result contains the road segments, each segment described by several points. These road segments represent a portion of the road with no intersections and the points follow the actual curve of the segment. Only the first and last points are kept by MINO as nodes with a corresponding road arc.

Additional data required for each road arc is available in the road shapefile and can be accessed using the ArcMap Attribute Table for the specific shapefile. The length of each road segment is extracted, as well as other data including the name of the road, e.g. County Road A10, and type of road, e.g. A5 – Vehicular Trail. The road name is informative for final analysis, and the road type is needed because certain roads cannot be used by normal vehicles. In particular, a road designated as A5, "Vehicular Trail" is usable only by four-wheel drive vehicles, and A7, "Road as Other Thoroughfare" is usable only by bicyclists or pedestrians: these read types are deemed unusable in MINO and omitted (U.S. Census Bureau 2001). For further Excel VBA processing, the shapefile's Attribute Table is exported and saved in dBase format (.dbf).

A VBA algorithm then processes the MapInfo file and dBase Attribute Table to create the road arc list by start node, end node, distance, road name, and road type. To further confine the road data to the working area and keep the dataset as small as possible, the road data is more accurately filtered by lat/long. Another filter also deletes any road of type A5 or A7. The resulting road-arc dataset contains essentially one-way only roads. To ensure traffic can flow either way on the road arcs, all roads are assumed to be two-way and a "reversed" copy of the arcs is added to the network during model

processing. (Internally, MINO uses a directed graph representation of the road network so every undirected arc (i, j) in G^{MINO} must be represented by the directed arcs (i, j) and (j, i).) A final road node list from the arc set is also maintained for connecting nodes that will represent population or ERS locations.

C. POPULATION MAPPING

Next, the human population is modeled and connected to the road network. From the TIGER database, census population data is provided for small geographical areas, referred to as "blocks." Downloading census block data requires the same process used for the road network: select counties and merge the county shapefiles into a single shapefile. Again, using ArcMap the census data is filtered by the Select Features tool. Since the population-processing algorithms place no restriction on the number of Census blocks in the final shapefile, the lat/long filtering can be done with a VBA filter (instead of using ArcMap).

Unlike the road network, the edges of the block shape cannot be transformed directly into a population network. Each block is represented by a node placed at the block's center with all population in the block assigned to that "population node." The shape's edge lat/long points are averaged to define a central population node that lies within the shape.

Creating population nodes follows the same initial steps as the road-network construction process. The merged shapefile for population census blocks is transformed into a MapInfo file. The MapInfo file is imported into Excel, processed, and averaged to create a set of population nodes. The actual population (number of people in a block shape) is captured by joining the demographic data with the merged shapefile's Attribute Table. The population data is copied in with the set of population nodes and the combined population set is filtered again. Some blocks contain no population, so nodes are not created for these. Nodes are also more accurately filtered by lat/long using a VBA algorithm. Next, population nodes containing five or fewer people are paired with neighboring, larger population nodes to reduce the total number of MINO nodes. This

"neighbor-population filter" reduces the number of population nodes by about ten percent.

Finally, the remaining set of population nodes must be connected to the road network. A search procedure finds the two closest road nodes, from the road node list, and arcs are created to these two nodes. To ensure these artificial arcs are not used to transit the network, other than to get the population on the road network or emergency responders to the population, a large distance penalty, C, is assigned to each one. The penalty C was chosen to be larger than any possible route within the MINO area. For all MINOs, $C = 100$.

D. EMERGENCY RESPONSE SYSTEM (ERS)

The ERS infrastructure data is provided by the National Geospatial-Intelligence Agency (NGA) from the Homeland Security Infrastructure Program database ("HSIP"; see NGA 2007). From the ERS data, locations are selected for two different ERS categories in a CF area. The emergency-responder (ER) category includes Emergency Medical Services (EMS), fire stations, and ambulance providers. The other category, referred to as "hospitals" here, actually includes hospitals and ambulatory surgical facilities.

These ERS data are provided as point shapefiles and locations are easily converted into nodes for MINO. For model simplicity, static locations are assumed for emergency-responders such as ambulance providers, which may normally preposition. As with population nodes, arcs are created to ensure these services and facilities connect to the road network for model analysis. These arcs are assigned actual distances, however.

APPENDIX C: GOOGLE EARTH NETWORK DISPLAY

A method to graphical depict the multi-infrastructure network operations model (MINO) is necessary to visually examine for accuracy and create results. At this point, then Google Earth (GE) is the solution. While ArcMap is useful to display initial shapefiles (ESRI 1998), after creating a MINO in Microsoft Excel with a standard arc set and node list, the MINO network cannot easily translate back into shapefile format for ArcMap display. Furthermore, ArcMap is not readily available for most DoD facilities and a more portable solution is desirable. Google Earth provides a simple solution. It encompasses an open-source set of tools than can quickly convert a standard network dataset of arcs and nodes into a useful graphical depiction. GE's built-in maps and other data provide a background image to correlate MINO to the actual geographic area and infrastructure.

Google Earth can display lines and points from a Keyhole Markup Language (KML) formatted whose format is similar to the more common Extensible Markup Language (XML). Generating a KML file from Excel requires a VBA macro to generate either arcs as lines or nodes as icons. The KML format is outlined in detail at the following Web site: http://code.google.com/apis/kml/documentation/index.html.

Node-name strings in MINO contain the node's latitude and longitude (lat/long) position in the network. For example, a road intersection or population group could be represented as the node string: "38.036284 -84.674312". With a single space between the two coordinates, Excel functions parse the latitude and longitude double-precision numerical values from the node name. The lat/long data along with the KML formatting create a file that GE can display. The following example, which results from processing that data for GE (Figure 33,) shows arc data in Excel and the KML file.

Tail Node	Head Node			<?xml version="1.0" encoding="UTF-8"?>
38.147029 -84.110742	38.148849 -84.110666	KML Export Arcs		<kml xmlns="http://earth.google.com/kml/2.1">
38.146641 -84.10741	38.147419 -84.107266			<Style id="road">
				<LineStyle>
				<color>FFFFFFFF</color>
				</LineStyle>
				</Style>
				<Placemark>
				<name>Network</name>
				<visibility>1</visibility>
				<open>0</open>
				<MultiGeometry>
				<styleUrl>#road</styleUrl>
				<LineString>
				<name>1</name>
				<extrude>0</extrude>
				<tessellate>1</tessellate>
				<coordinates>
				-84.110742,38.147029,0
				-84.110666,38.148849,0
				</coordinates>
				</LineString>
				<LineString>
				<name>2</name>
				<extrude>0</extrude>
				<tessellate>1</tessellate>
				<coordinates>
				-84.10741,38.146641,0
				-84.107266,38.147419,0
				</coordinates>
				</LineString>
				</MultiGeometry>
				</Placemark>
				</kml>

Figure 33. Google Earth Arc-to-KML Example.
In this figure, the nodes on the left represent two road arcs, each described with a "tail node" and "head node," in the MINO network. The VBA macro creates the KML arc file which can be displayed in Google Earth. The right column of the figure shows the actual KML generated for the two specific arcs on the left.

Figure 34 shows the VBA code that creates a KML file for MINO nodes, and Figure 35 shows the VBA code that creates a KML arc file.

```
Sub Nodes2KML()
    Dim rNodes As Range, FN As Integer, i As Long, j As Long
    Dim dLat As Double, dLong As Double
    Set rNodes = ActiveSheet.Range("I2", ActiveSheet.Range("I2").End(xlDown).End(xlToRight))
    ChDrive Left$(ActiveWorkbook.path, 1)
    ChDir ActiveWorkbook.path
    FN = FreeFile()
    Open "nodes.kml" For Output As FN
    Print #FN, "<?xml version=""1.0"" encoding=""UTF-8""?>"
    Print #FN, "<kml xmlns=""http://earth.google.com/kml/2.1"">"
    Print #FN, "<Document>"
    For i = 1 To rNodes.Rows.Count
        Print #FN, "<Placemark>"
        Print #FN, "  <name>i</name>"
        Print #FN, "    <Point>"
        Print #FN, "      <coordinates>"
        dLat = Latitude(rNodes(i, 1))                 'Latitude function
        dLong = Longitude(rNodes(i, 1))               'Longitude function
        Print #FN, "      " & dLong & "," & dLat & "," & 0
        Print #FN, "      </coordinates>"
        Print #FN, "    </Point>"
        Print #FN, "</Placemark>"
    Next i
    Print #FN, "</Document>"
    Print #FN, "</kml>"
    Close FN
End Sub
```

Figure 34. VBA Code Converting Nodes into Google Earth KML Files.

```
Sub Network2KML()
    Dim rArcs As Range, rNodes As Range, FN As Integer, i As Long, j As Long
    Dim dLat As Double, dLong As Double

    'Sets range of arcs to convert to into KML
    Set rArcs = ActiveSheet.Range("A2", ActiveSheet.Range("A2").End(xlDown).End(xlToRight))
    ChDrive Left$(ActiveWorkbook.path, 1)
    ChDir ActiveWorkbook.path
    FN = FreeFile()
    Open "network.kml" For Output As FN    'Output file name in same dir as Workbook
    Print #FN, "<?xml version=""1.0"" encoding=""UTF-8""?>"
    Print #FN, "<kml xmlns=""http://earth.google.com/kml/2.1"">"
    Print #FN, "<Style id=""road"">"            'Sets line color (white)
    Print #FN, "  <LineStyle>"
    Print #FN, "    <color>FFFFFFFF</color>"
    Print #FN, "  </LineStyle>"
    Print #FN, "</Style>"
    Print #FN, "<Placemark>"
    Print #FN, "<name>Network</name>"
    Print #FN, "<visibility>1</visibility>"
    Print #FN, "<open>0</open>"
    Print #FN, "<MultiGeometry>"
    Print #FN, "<styleUrl>#road</styleUrl>"
    For i = 1 To rArcs.Rows.Count
        Print #FN, "    <LineString>"
        Print #FN, "      <name>" & i & "</name>"
        Print #FN, "      <extrude>0</extrude>"
        Print #FN, "      <tessellate>1</tessellate>"
        Print #FN, "      <coordinates>"
        For j = 1 To 2
            dLat = Latitude(rArcs(i, j))          'Latitude function
            dLong = Longitude(rArcs(i, j))        'Longitude function
            Print #FN, "      " & dLong & "," & dLat & "," & 0
        Next j
        Print #FN, "      </coordinates>"
        Print #FN, "    </LineString>"
    Next i
    Print #FN, "</MultiGeometry>"
    Print #FN, "</Placemark>"
    Print #FN, "</kml>"
    Close FN
End Sub
```

Figure 35. VBA Code Converting Arcs into Google Earth KML Files.

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